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AFATL-TR-77-1, VOLUME II

INVESTIGATION OF OBLIQUE SHOCKS AND EDGE EFFECTS FOR UNDERGROUND TARGETS
VOLUME II. EDGE EFFECTS

ORLANDO TECHNOLOGY, INCORPORATED
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JANUARY 1977

FINAL REPORT: DECEMBER 1975 - JUNE 1976

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)
This report summarizes results of a four-month test and analysis program to establish maximum breach distances for explosives placed at several positions about the corner of a buried concrete structure. The objective of the program was to generate test data showing explosive charge stand-off distances at which buried concrete structures will be breached for charges placed on the corner diagonal, the corner shear line, and the mid-span of the wall.

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Composition C-4 explosive charges were detonated against high strength concrete cubicles with walls 4 and 8-inches thick. One-third scaling was used for all tests, and quartz pressure transducers recorded force and impulse data on the target wall and in the free soil. Results of the study showed that difficulty of breaching the walls of the buried concrete targets increase dramatically as the explosive charge is moved from mid-span to shear line to diagonal positions. For the 4-inch concrete walls, 4 pounds of explosive at 2-foot stand-off breached the wall from the mid-span position, a 1-foot stand-off was required for 4 pounds of explosive on the shear line, and 10 pounds of explosive was required for a 1-foot stand-off on the diagonal. For the 8-inch concrete walls, a 10-pound charge breached the wall at a 1-foot stand-off from the mid-span, and actual contact between charge and wall was required from the shear line position. A 10-pound contact charge did not damage the wall from the diagonal position, but 27 pounds of explosive in contact breached the target. Breach contours were developed from analysis of the entire data base, and a function was derived to relate maximum breach distance to explosive charge weight and position. Recommendations are to initiate use of these findings in target vulnerability analysis of high explosive munitions encountering underground concrete structures.

PREFACE

This report summarizes analytical and experimental investigations conducted from June 1976 through September 1976 by Orlando Technology, Inc., 6237 Edgewater Drive, Orlando, Florida 32810, under Contract F08635-76-C-0155, Investigation of Oblique Shock and Edge Effects for Underground Targets with the Air Force Armament Laboratory, Armament Development and Test Center, Eglin Air Force Base, Florida. Mr. G. Rickey Griner (DLYV) managed the program for the Armament Laboratory.

This report consists of two volumes. Volume I contains results of experimentation to establish effects of oblique shock waves on buried concrete structures. and Volume II presents experimental results of tests to determine breach distance in the corner region of buried concrete structures. This is Volume II.

Orlando Technology Inc. Program Manager was Dr. Hans R. Fuehrer. Mr. John W. Keeser, Jr. was a principal contributor.

This technical report has been reviewed and is approved for publication.

FOR THE COMMANDER:

JR Murray

J. R. MURRAY
Chief, Weapon Systems Analysis Division

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SECTION I

INTRODUCTION

This introductory section presents objectives of work reported in this volume, followed by the organization of remaining sections.

A. OBJECTIVE

The objective of the experimental program reported herein was to generate test data to ascertain the effects of underground explosive charges detonating near the corner of buried cubicle concrete structures.

B. REPORT ORGANIZATION

This volume presents free-soil test data and results of tests conducted against cubical underground structures to ascertain the effects of explosive charges on these structures when explosive charges are detonated near the corner of the structures. Section II of this volume presents data on tests done to determine effects of charge orientation. Section III presents the results of the underground structure tests where both 4-inch and 8-inch-thick wall structures are used. Data analysis and conclusions are presented in subsection III-D. Section IV summarizes the conclusions and recommendations.

SECTION II

FREE-SOIL DATA

A brief set of experiments were conducted to determine whether the orientation of a cylindrical charge has an effect on the soil overpressure at a specific point.

A. TEST SET-UP

A test arrangement was devised in which pressure measurements can be made in the soil at several positions relative to a cylindrical explosive charge. A cylindrical charge of composition C-4 with L/D of 3 was buried 3 feet deep with its long axis horizontal. The charge weighed 4 pounds. Two Kistler 907A quartz pressure gages were buried at the same depth as the explosive charge. One gage was placed on the long axis of the cylinder with its measuring surface perpendicular to the long axis. The front surface of the gage was 8 feet from the end of the cylinder. The other gage was placed on the perpendicular to the long axis of the cylinder with its measuring surface parallel to the long axis. The front surface of this gage was 8 feet from the side of the cylinder. Figure 1 shows the test configuration.

This pressure gage configuration measured the pressure transmitted through the soil from the end and side of the explosive cylinder. Each gage was rigidly mounted to a 2-inch-thick by 12-inch-diameter steel disk. The disk provided a rigid nonmoving support for the gage. Soil (damp, undisturbed sandy loam) was firmly tamped around the gage-disk assembly, and care was taken to insure that the explosive cylinder and gages were in the same plane. Orientation of the gages relative to the cylinder was verified to be at a right angle.

The output from each gage was fed into a Kistler-type 504E charge amplifier which, in turn, drove a Type 1A1 amplifier in a Tektronics 555 oscilloscope. The horizontal sweep (external setting) of the scope was triggered by an ionization switch buried in the explosive charge. Subsection III-A of Volume I has a complete description of the instrumentation used. The outputs of the end and side gages were reversed after each test. This reversal was done to eliminate possible bias one channel may have had. A total of three tests were run.

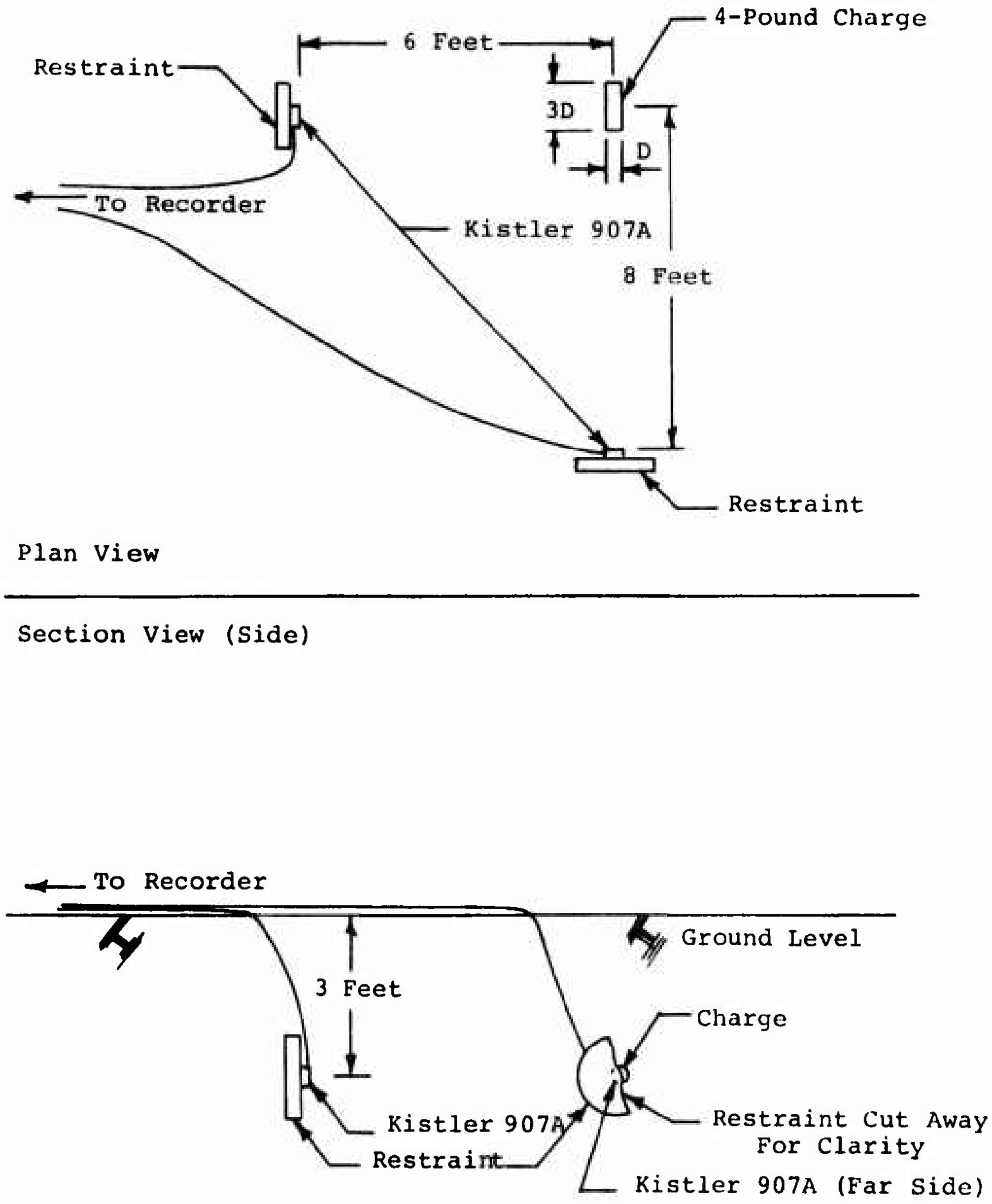


Figure 1. Free Soil Test Set-Up

B. TEST RESULTS

The results of the three tests gave an average side-to-end force ratio of 5 to 1. The average side force for three tests was 352 pounds (159.7 kilograms). Data for forces off the end of the charge was obtained from two tests. The average end force for the two tests was 70 pounds (31.75 kilograms). In all cases, the gage area was 7 square inches (47.16 square centimeters).

Free-soil shock velocity was also measured by noting the time delay from detonation to the beginning of the pressure pulse. The average delay of five traces was found to be 15.62 milliseconds. Dividing this into the charge-to-gage distance of 8 feet (2.03 meters) gave 512 feet per second (130 meters per second).

This free-soil shock velocity was found to be in general agreement with velocities measured in Volume I, subsection III-B, using a single buried gage and 250 grams of explosive. The soil used for all of these tests had an average density of 104.6 pounds/cubic feet (1.68 grams per cubic centimeter). It contained sufficient moisture to retain its shape when squeezed into a ball, but no excess water was expelled. The composition was Central Florida sand with some organic material.

SECTION III

UNDERGROUND STRUCTURES TESTS

A total of 23 tests were conducted against reinforced concrete structures to determine the failure (breach) modes as a function of explosive charge weight and position. The configurations selected were one-third scale models of typical reinforced concrete underground structures. They were made in the shape of a square open-ended cube from high strength reinforced concrete. Scaled wall thicknesses of 4 inches (10.2 centimeters and 8 inches (20.3 centimeters) simulated full-size thicknesses of 1 and 2 feet (0.254 and 0.610 meters), respectively. The steel-to-concrete area ratio was set at two percent to correspond with accepted practice for blast-resistant structures. The height and length of the sides were approximately 5 feet (1.52 meters). Wall height was selected so that explosive charges could be buried midway down the wall and have sufficient overburden to constrain the explosion until shock impinged on the wall.

Charge weights used were 4, 10, and 27 pounds (1.81, 4.54, and 12.25 kilograms at stand-off distances from contact to 4 feet (1.22 meters). The 4- and 10-pound charges were detonated against the 4-inch wall thickness box. The 4-, 10-, and 27-pound charges were used against the 8-inch wall thickness box. Appendix A provides photographs and data for each test. Subsections A through D below present the physical test arrangement, 8-inch wall results, 4-inch wall results, and conclusions.

A. TEST ARRANGEMENT

This subsection outlines the design, construction, emplacement, and instrumentation used for the buried concrete structure testing.

1. Target Design

Buried blast-resistant (hardened) structures having wall thicknesses of 1 (0.254 meters) and 2 feet (0.610 meters) were selected as being representative of the class of target most likely to be encountered by conventional high explosive munitions. A scaling factor of three was chosen for the model. This factor gave scaled wall thickness of 4 and 8 inches (10.2 and 20.3

centimeters). The full-scale wall length of 15 feet (4.57 meters) was scaled down to 5 feet (1.52 meters). Grade 40 structural steel was used for the reinforcing in each box.

The boxes were manufactured by Dura-Stress, Inc. Leesburg, Florida, at their Leesburg facility. Test cylinders were taken for each box per ASTM standards and compression tested by Dura-Stress at their state-approved facility. All test cylinders exceeded a compression strength of 6000 psi (421.8 kg/cm^2) 17 days after casting.

The concrete was placed into steel molds and vibrated into place around the reinforcing steel to obtain a void-free wall structure. The surface finish of the boxes was smooth with little or no roughness. Figure 2 is the fabrication design for the 4- and 8-inch wall thickness boxes. The corners had additional shear reinforcement placed at a 45-degree angle to carry the bending moments around the corners. All of the steel was tied together at least 50 percent of its crossover points with wire ties. Lifting loops were cast into the top to facilitate placement in the test arena.

2. Test Geometry

The test configuration consisted of a box (open end vertical) buried so that its top surface was even with the ground level (Figure 3). Soil was backfilled around the perimeter and compacted to simulate undisturbed fill. The interior volume of the box was void of soil from its lower edge to simulate the interior of a buried structure. The explosive charge and soil-pressure gages were both buried at a depth equal to one-half of the box wall height. The explosive charge was placed in one of three areas: (1) midspan or midway between the two corners and on a normal to the wall; (2) shearline or on a normal to the wall but offset from the corner the thickness of the wall; or (3) corner diagonal or along the 45-degree diagonal passing through the two opposite corners.

The stand-off distance was measured from the center of the explosive charges to the nearest point on the test structure surface. Three soil-pressure gages were used for the tests. One gage was placed in contact with the test structure with its sensing direction normal to the wall. The gage-to-charge distance was approximately equal to the charge stand-off distance. Two other gages were buried in the free-soil at distances of 1X and 2X (X being dependent on the charge size but never less than 4 feet (1.22 meters).

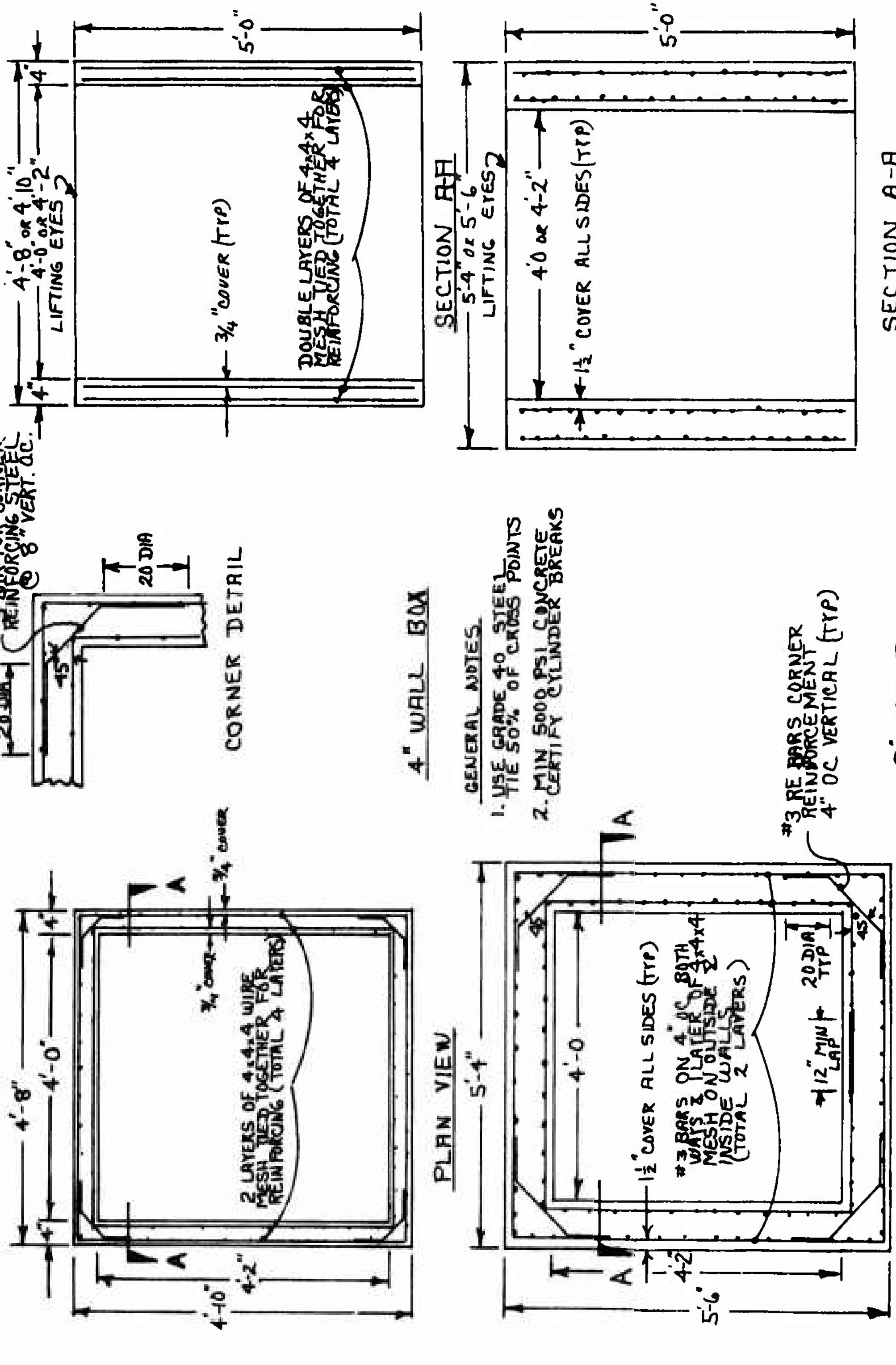
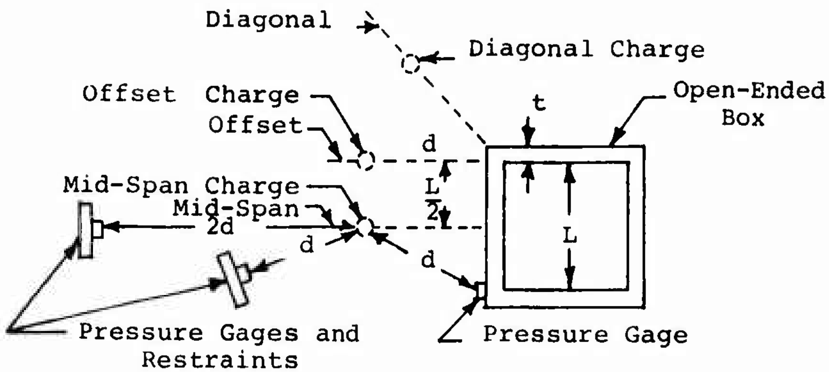


Figure 2. Box Design Fabrication Drawing



This sketch depicts all three possible charge locations. The gage positions for a mid-span placement are also shown.

Plan View

Section View

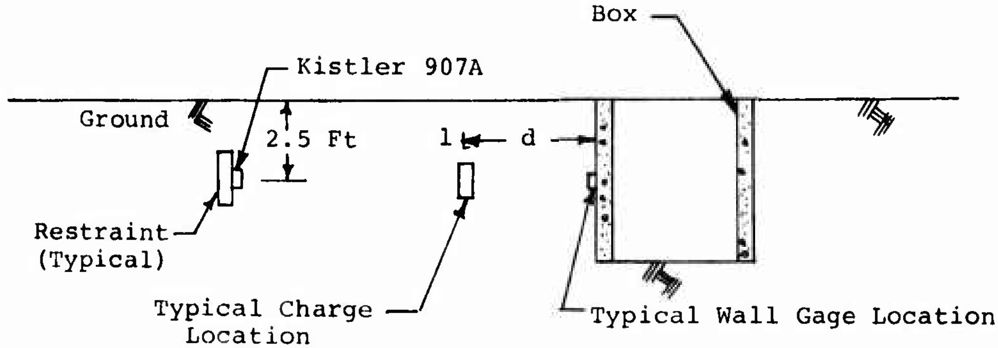


Figure 3. Underground Structure Test Lay Out

The sensing direction of the free-soil gages was always normal to the shock pulse so as to obtain maximum pressure values. The free-soil gages were rigidly attached to a large steel disk (Figure 4). The disk provided a rigid body for the gage to push against when impacted by the pressure pulse.

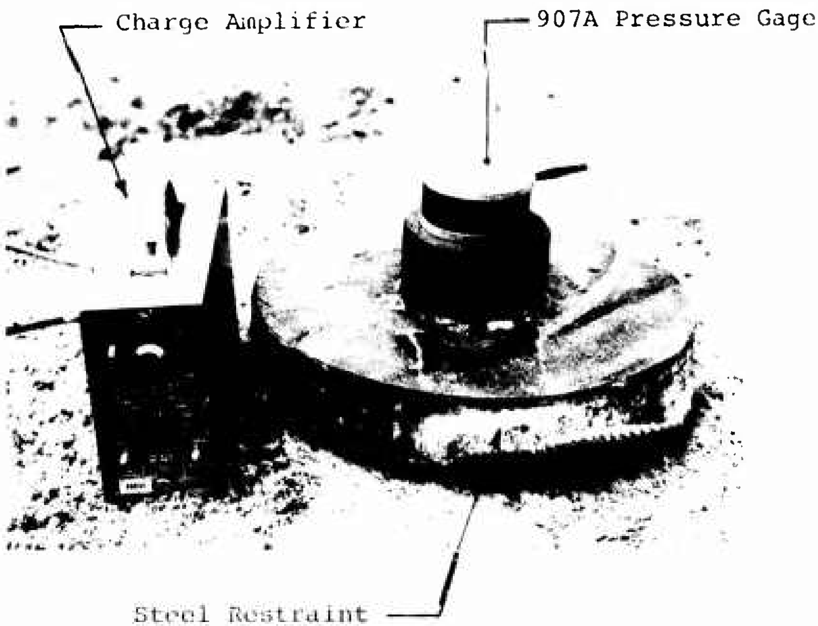
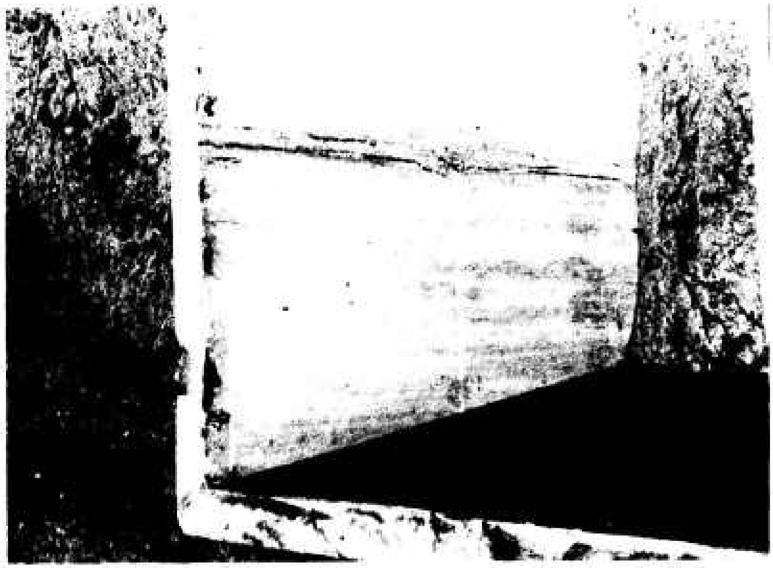
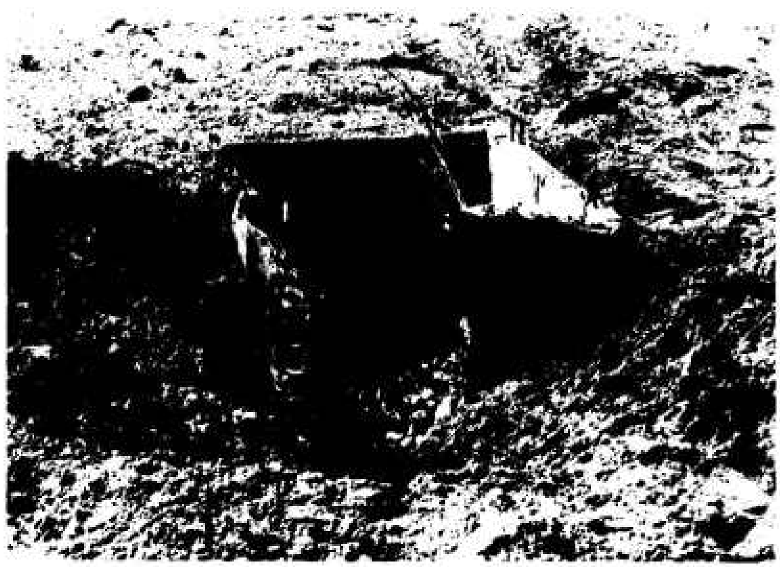


Figure 4. Pressure Gage and Restraint

A breach/no-breach condition was used to evaluate results of each test. Breach was defined as a physical hole through the reinforced concrete structure. It was not necessary for the



(A) No-Breach



(B) Breach

Figure 5. Typical (A) No-Breach, and (B) Breach Configurations

steel reinforcing to fracture for breach to occur, but in all breach cases, steel fracture actually did occur. A no-breach condition existed whenever structural integrity was maintained (i.e., no through holes) even though heavy fracture and spalling may have occurred. Partial wall collapse was not recorded as a breach unless the structure could not be re-used for its intended purpose. Figure 5 illustrates breach and no-breach conditions.

3. Instrumentation

With the exception of the physical gage spacing, the instrumentation used for the force measurements was the same as that used for the Phase I testing. Figure 6 presents a typical oscilloscope trace of a pressure profile. Volume I, which documents the results of the first phase of this program, provides details of the gages.

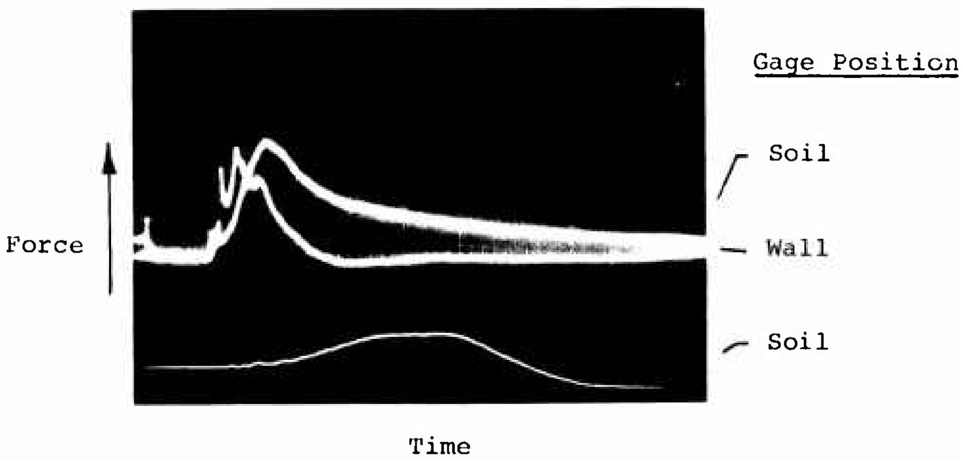


Figure 6. Typical Oscilloscope Data (Test 7)

B. TEST RESULTS FOR EIGHT-INCH WALLS

Fifteen tests were conducted against the 8-inch-(20.3-centimeters) thick wall cubical structures. Table 1 lists each test with explosive weight and position. Stand-off and results are also tabulated in Table 1. Breach conditions were obtained with five of these tests. (Breach is defined as completely removing concrete from the wall so that soil is exoposed to the interior of the structure.)

Figure 7 is a graphical summary of the tests. The cubical structure as viewed from the top is shown in the center. The results of 4-pound (1.82 kilograms) charge tests are shown in the upper right-hand corner of Figure 7. The data shows that the 4-pound charge, even in contact (test 4), was not capable of breaching the 8-inch wall structure from the diagonal position.

In the upper left-hand corner, the results of the 10-pound (4.54 kilogram) charge tests are shown. Here again, the 10-pound charge in contact with the structure was unable to breach the wall from the corner position (test 6). However, when the charge was moved to the shear line position, it was capable of breaching the structure. Also, when the 10-pound charge was moved to the midspan position with 1-foot (0.254 meters) stand-off, breaching occurred, whereas with a 2-foot (0.610 meters) stand-off, breaching did not occur.

The 27-pound (12.25-kilogram) charge placed in contact with the corner was capable of breaching the structure. This set-up caused massive damage to the target structure. The 27-pound charge at a 2-foot (0.610-meters) stand-off from the mid-span and shear line also resulted in a target breach.

Pressure measurements were recorded as described earlier and are tabulated in Table 2 for all experiments with the 8-inch wall structures.

C. TEST RESULTS FOR FOUR-INCH WALLS

Eight tests were conducted against 4-inch (10.2-centimeters) wall test structures. Table 3 lists explosive charge weight and location for each of these tests. In addition, the stand-off distance and results of each test are given in Table 3.

TABLE 1. TEST RESULTS FOR EIGHT-INCH WALL TARGET

Test	Charge Weight (pounds)	Location	Stand-off (feet)	Results
1	4	(1)	4	No damage
2	4	(1)	3	No damage
3	4	(1)	2	Slight cracking in corner
4	4	(1)	Contact	Slight cracking and spalling
5	10	(1)	3	No damage
6	10	(1)	Contact	Heavy interior spalling
7	10	(2)	1	Reinforcing steel uncovered
8	10	(2)	Contact	Breached wall
9	10	(3)	2	Slight spalling
10	10	(3)	1	Breached wall
11	27	(1)	3	Slight cracking at corners
12	27	(1)	Contact	Breached with heavy wall damage
13	27	(2)	3	Heavy spalling and cracking
14	27	(2)	2	Breached wall
15	27	(3)	2	Breached wall

Note:

(1) Charge located along diagonal drawn through two opposite corners.

(2) Charge located normal to wall and offset from corner at a distance equal to wall thickness.

(3) Charge located at mid-span of wall.

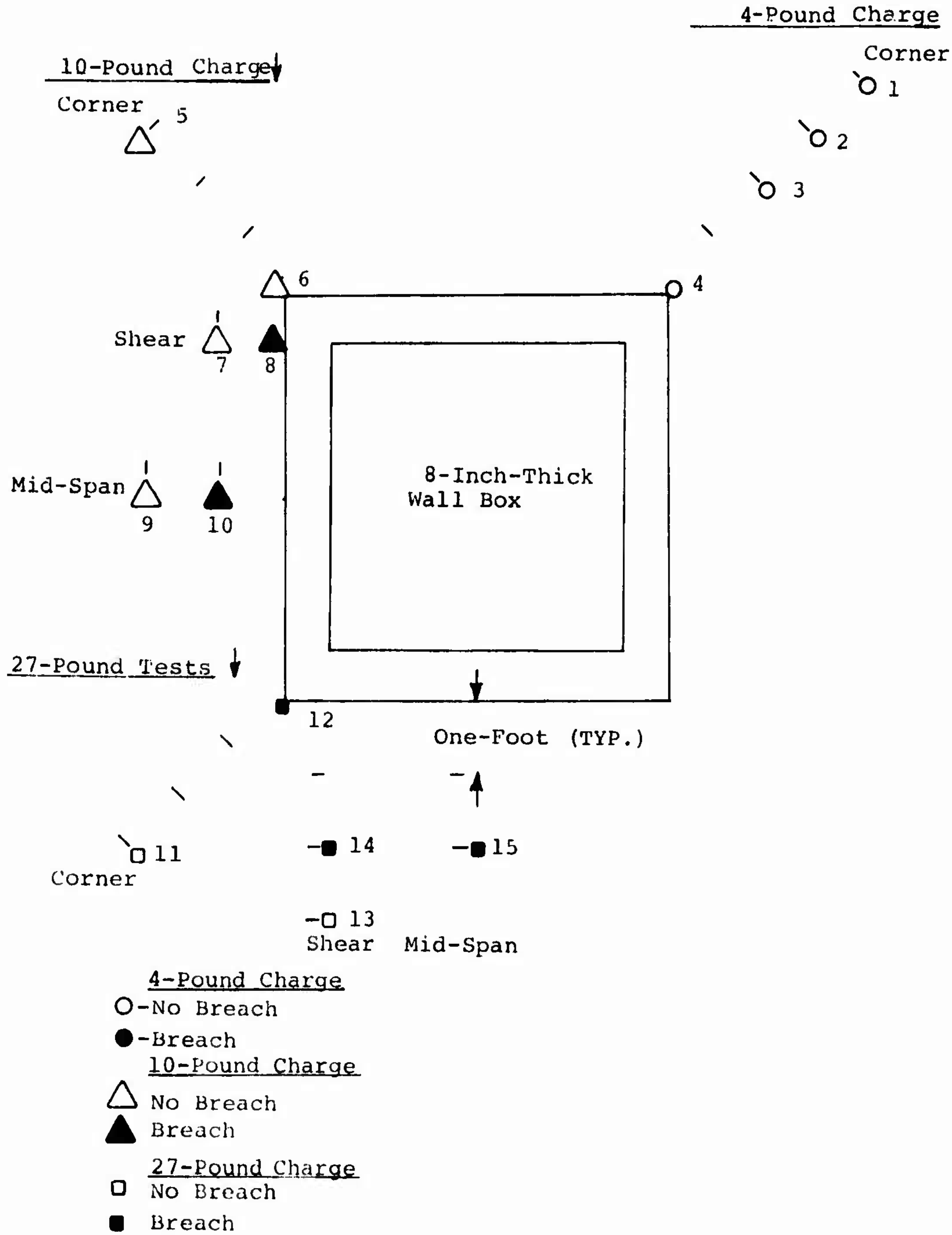


Figure 7. Test Results for Eight-Inch Wall Target

TABLE 2. SOIL PRESSURE AND TOTAL IMPULSE FROM TESTS AGAINST 8-INCH WALL TARGET

Test Number	Gage Location	Gage Stand-off[1] (feet)	Total Force (pounds)	Total Impulse (pound ms)	Angle of Incidence[2] (degrees)	Notes
2	Soil	5.25	466	10,888	NA	Back filled, compacted soil, damp, not wet
	Soil	10.9	209	5,351	NA	
	Wall	5.25	257	14,434	67	
3	Wall	4.67	361	1,182	71	
4	Soil	10	299	8,213	NA	Back filled, compacted soil, damp, not wet
	Wall	3	423	2,034	90	
5	Wall	5.3	748	7,777	67	
6	Soil	4.67	1,411	51,950	NA	Back filled, compacted soil, damp, not wet
	Soil	10.5	169	2,551	NA	
7	Wall	4.8	722	3,061	78	
9	Wall	3.4	3,274	15,368	53	
11	Soil	8	282	3,017	NA	Back filled, compacted soil, dry
	Soil	8	621	24,017	NA	
12	Soil	10.5	705	19,598	NA	Back filled, compacted soil, dry
13	Soil	12	339[(3)]	6,220[(3)]	NA	
14	Soil	12	1,208	21,900	NA	
15	Soil	16	127	4,355	NA	Back filled, compacted soil, dry

Notes:
1. Distance measured from charge center to gage surface.
2. A 90-degree angle is when the gage axis is parallel to shock front.
   A 0-degree angle is when the gage axis is perpendicular to shock front.
3. Highest reading obtained prior to trace going off-scale on oscilloscope.

TABLE 3. TEST RESULTS FOR FOUR-INCH WALL TARGETS

Test	Charge Weight (pounds)	Location	Stand-Off (feet)	Results
16	4	(1)	2	Some wall cracks - no spalling
17	4	(1)	1	Six-inch wall deflection; one-half inch cracks - no spalling
18	4	(2)	3	Hairline corner cracks - no spalling
19	4	(2)	1	Breached wall
20	4	(3)	4	Slight corner cracking - no spalling
21	4	(3)	2	Breached wall - fractured some steel bars
22	10	(1)	3	Slight wall cracking - no spalling
23	10	(1)	1	Breached wall and flattened corner of structure

Notes:

(1) Charge located along diagonal drawn through two opposite corners.

(2) Charge located normal to wall and offset from corner a distance equal to wall thickness.

(3) Charge located at mid-span of wall.

Figure 8 graphically illustrates the results of each test. The 4-pound (1.81-Kilogram) charge at 1-foot (0.254 meters) stand-off did not breach the wall at the corner but did breach the structure from the shear line. Further, the 4-pound (1.81 Kilogram) charge was capable of breaching the structure from the midspan position.

The next set of tests showed that 10 pounds (4.54 kilograms) will breach the structure with 1-foot (0.254 meters) stand-off from the corner. Three breach points were obtained with the eight tests conducted. Table 4 lists pressure and total impulse in the soil for tests conducted with the 4-inch walls.

D. ANALYSIS AND CONCLUSIONS

A total of 23 tests were conducted to evaluate the effects of explosive charges detonated at several positions about the corner of an underground cubical structure. Demolition data can be used to estimate the charge weight required to breach concrete box structures. For contact charges, the breaching explosive weight is given by Reference 1 to be:

$$P = R^3 KC/1.34$$

where P is weight of C-4 charge (pounds)

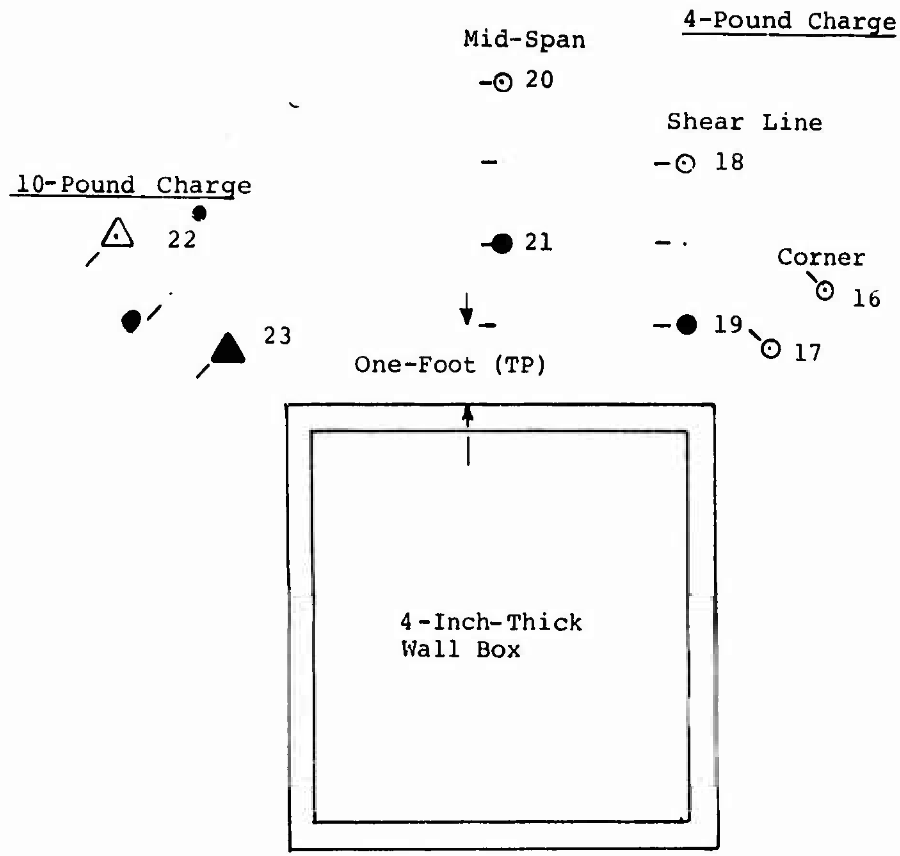
R is breaching ratings (feet)

K is material factor (1.76 for the test structures considered here)

C is tamping factor (1.0 for these tests)

For an 8-inch-thick wall, 0.4 pound of C-4 are required to breach the wall. For the corner where one must breach through the diagonal, the charge weight increases to 1.1 pounds accordinc to this formula. Based on the test data, this formula appears invalid since a 10-pound charge of C-4 was incapable of breaching the wall from the corner.

In order to establish whether pressure levels were being generated consistent with that expected from these types of C-4 charges, a plot of force versus the scaled distance was made. These data are shown in Figure 9, using the information tabulated



Legend:

4-Pound Charge
O - No Breach
● Breach

10-Pound Charge
△ No Breach
▲ Breach

Figure 8. Test Results for Four-Inch Wall Target

TABLE 4. SOIL PRESSURE AND TOTAL IMPULSE FROM TESTS AGAINST FOUR-INCH TARGETS

Test	Gage Location	Gage Stand-off[1] (feet)	Total Force (pounds)	Total Impulse (pound ms)	Angle of Incidence[2] (degrees)	Notes
16	Wall	3.5	1,612	65,610	53	Undisturbed soil
18	Soil	8	200	6,900	NA	Saturated soil - undisturbed
	Wall	6	200	6,900	60	
19	Soil	4	2,200	14,460	NA	Saturated soil - undisturbed box used for test 18
	Soil	8	135	3,111	NA	
	Wall	5.6	675	14,980	69	
20	Soil	4	1,890	35,263	NA	Saturated soil - partially disturbed box used for tests 18 and 19 previously
	Soil	8	244	7,250	NA	
	Wall	4.9	555	15,634	35	
21	Soil	4	2,278	25,436	NA	Completely back-filled box area. Box used for tests 18, 19, and 20 previously.
	Soil	8	278	8,619	NA	
	Wall	3.5	1,612	65,610	53	
22	Soil	6	3,000	54,906	NA	Saturated soil - undisturbed
	Soil	12	212 (3)	3,795 (3)	NA	
	Wall	5.3	733	13,684	67	
23	Soil	6	1,298	17,598	NA	Saturated soil - undisturbed
	Soil	12	113	---	NA	Box used for test 22 previously
	Wall	3.5	267	9,870	79	

1. Measured from charge CG to gage surface.
2. A 90-degree angle is when gage axis is parallel to shock front; a 0-degree angle is when gage axis is perpendicular to shock front.
3. Highest reading obtained prior to trace going off-scale.

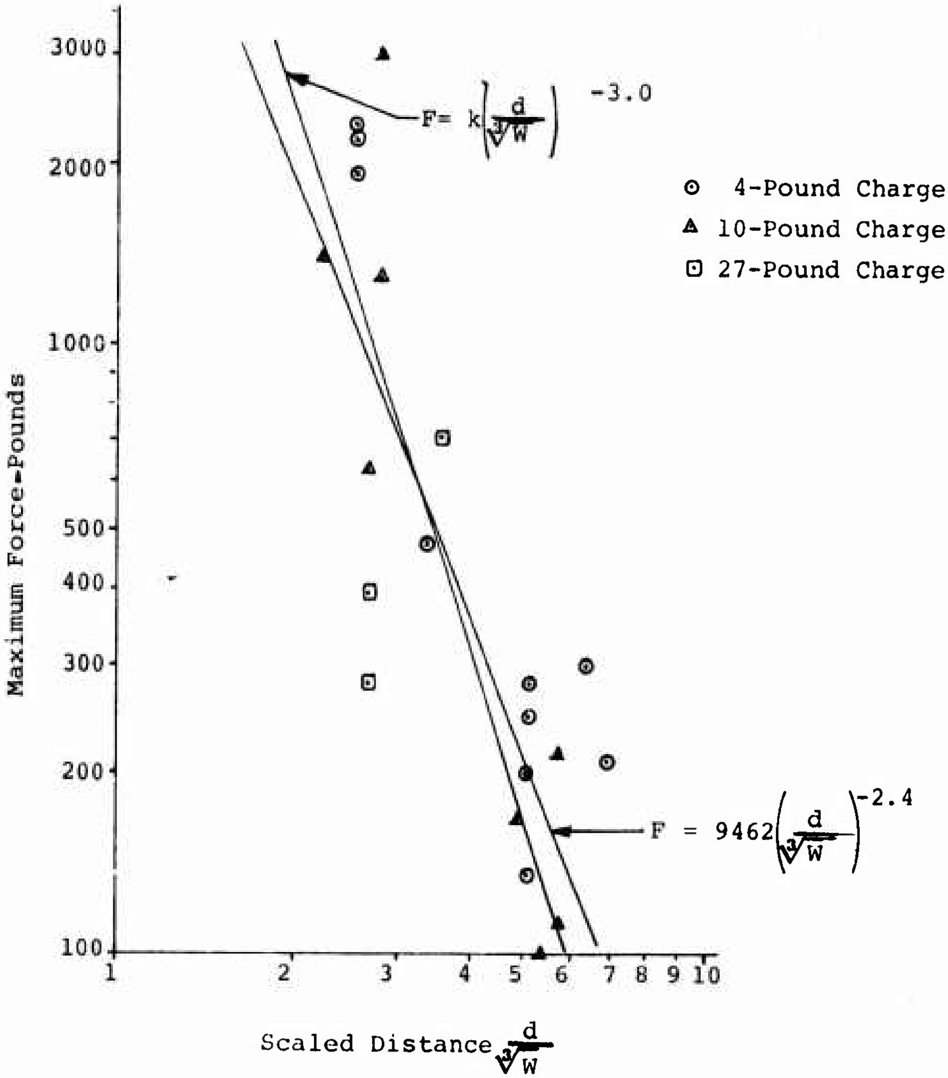


Figure 9. Maximum Force Versus Scaled Distance

in Tables 2 and 4. A least-squares fit for the data shows that force decreases as the inverse 2.4 power of scaled distance. This value is in contrast to the inverse cube type of scaling which is usually employed. However, with the scatter in the data, the inverse cube plotted in Figure 9 is not an unrealistic relation.

Figure 10 shows the results of tests done during World War II by the Home Security and Road Research Laboratory (British) and by the Committee on Fortification Design (USA). This information is based on test walls whose face dimensions are in the ratio of about 3:5, and whose span-to-thickness ratio is between 5:1 and 15:1. The test walls were reinforced with mild steel bars, about one percent by volume. Damage and central deflection were measured for bombs detonated at various distances on the earth side of the wall. Charge weights used in these tests ranged from 1/3 pound to 1,000 pounds. Figure 10 presents the breaching distance as the function of wall thickness where both are scaled by the charge weight cube root. These tests were conducted against the mid-span. Mid-span data are also given for tests conducted in this program.

From this data it can be seen that the breaching points lie far below the World War II data, as should be expected, since these tests were conducted with two percent reinforcing steel as is the current recommended design as opposed to one percent steel used in the World War II data. Span-to-thickness ratio is 6:1 for the 8-inch-thick wall and is 12:1 for the 4-inch-thick wall. Both fall within the World War II data range.

Using this same type of format, Figure 11 plots the test data generated in this program. Here the trend to reduced standoff distances as the charge is moved to the corner can be seen for both breach and no-breach conditions.

Data from the 4-inch-thick walls can be scaled up by a scale factor of two to give comparable results with the 8-inch-thick wall data. Table 5 gives a summary of this data where 32-pound and 80-pound values are scaled 4-pound and 10-pound charge data.

In certain cases, the damage was such that an overkill condition existed. For example, the 27-pound charge did more than just breach the structure i.e., expose the interior to exterior soil. Thus, the zero distance or contact charge at the corner must be viewed as unrealistically small. The same is

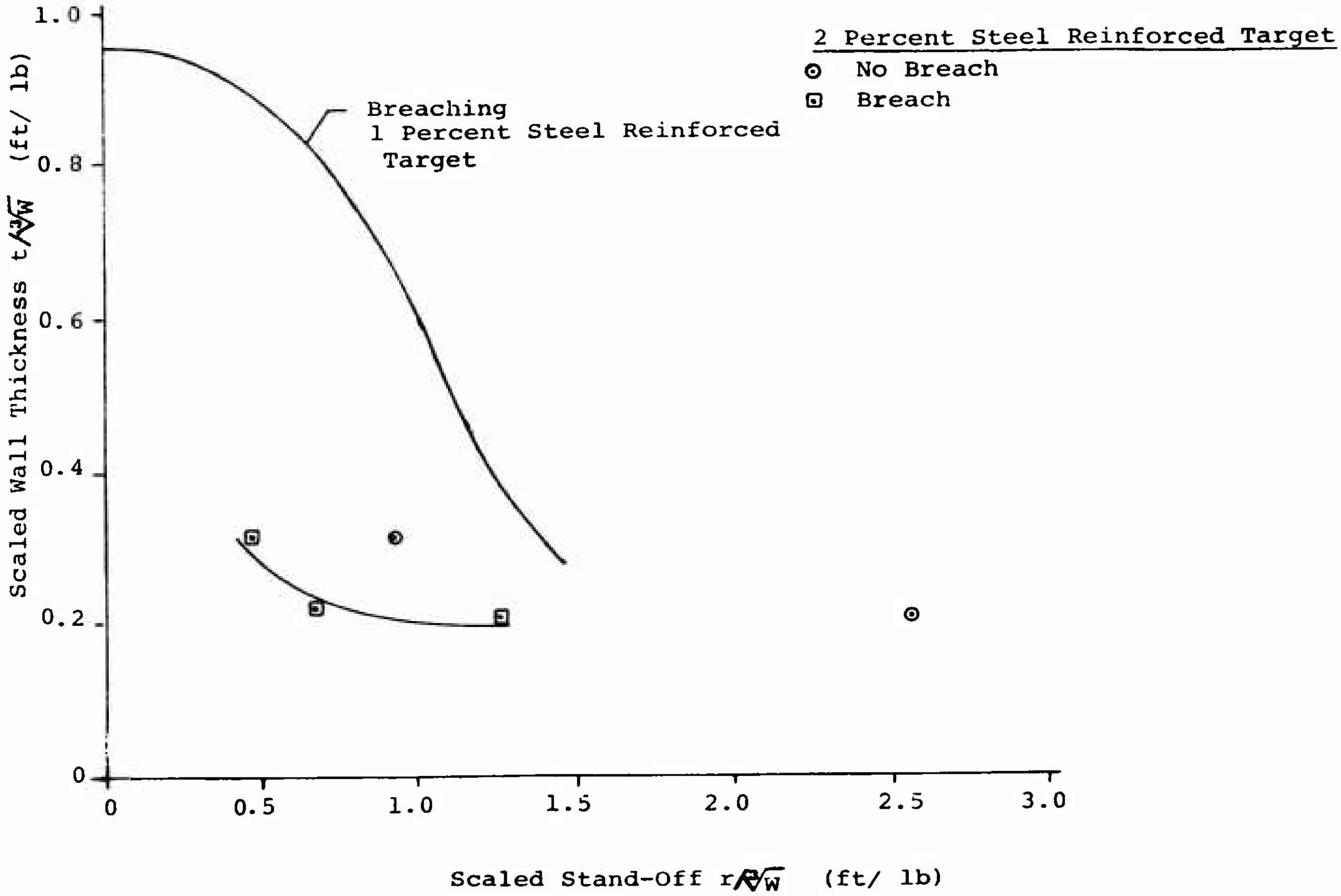


Figure 10. Mid-Span Breaching Data

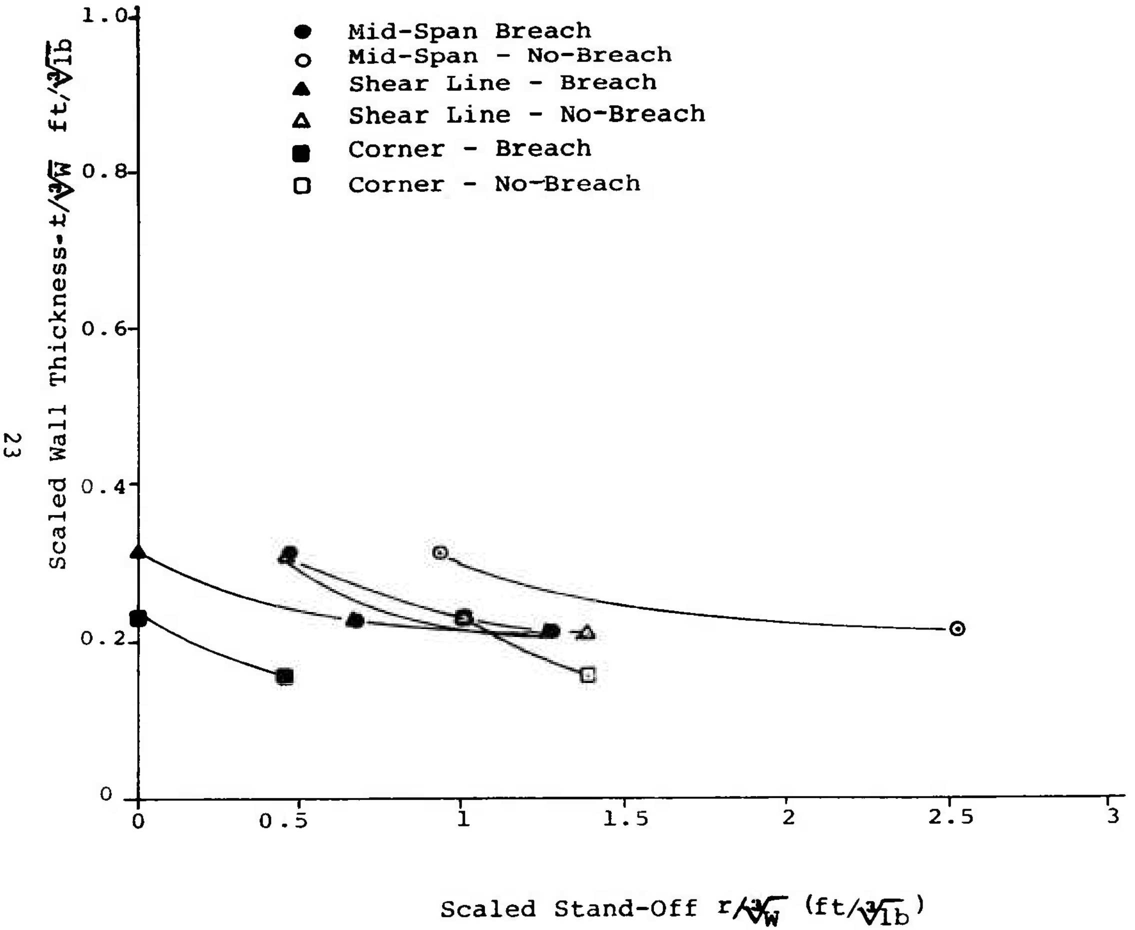


Figure 11. Scaled Test Data Generated During This Program

true with the 27-pound charge breach distance of 2 feet at the midspan. The converse is also true: some of the no-breach distances failed to cause even heavy cracking at the specific distance. For example, at the corner with 3 feet stand-off, very little damage was done by the 27-pound charge.

TABLE 5. TEST DATA SCALED TO EIGHT-INCH TARGET WALLS

Charge Weight (pounds)	Charge Location	Breach Distance (ft)	No-Breach Distance (ft)
4	Corner	None	-
10	Corner	None	-
27	Corner	0	3
32	Corner	-	4
80	Corner	2	6
10	Shear Line	0	1
27	Shear Line	2	3
32	Shear Line	2	6
10	Mid-Span	1	2
27	Mid-Span	2	-
32	Mid-Span	4	8

Note: - indicates no test point data available.

In review of the data, it was found that when one approached the corner, a charge had to be moved close to obtain equivalent damage. Here again a subjective evaluation had to be made. The failure mode at mid-span was different from that found at the corner. Where mid-span failure was typically hinge point failure, corner failure modes showed substantial compression failure in the walls.

In light of this information and the specific data, the following formulation is suggested:

$$R \text{ (breach)} = k_s \, k_c \, R \text{ (mid-span)}$$

where R (breach) is distance from charge center to closed point on wall (feet)

R (midspan) is longest stand-off distance from charge center to mid-span point from which breach will occur (feet)

k_s is span factor

k_c is corner factor.

This formulation is based on the following considerations:

(1) As the charge moves away from the mid-span toward the corner, the charge pressure pulse encounters less wall area and becomes an offset load. More load is carried by the side walls due to the offset. Both of these effects reduce the breach distance. Because of geometrical effects, the reduction in wall loading area may not become effective until the charge nears the shear line. For point-beam loading with fixed ends, the bending moment decreases linearly. The effective area for the walls also decreases essentially linearly as the charge moves away from the mid-span point. This relation sugfests a linear decreasing function span factor such as:

$$K_s = (l - a)/l$$

where l is span length

a is transverse distance of charge from mid-span position.

This function reduces shear line breach distance to one-half the mid-span breach distance as is consistent with the test observations.

(2) When the charge is detonated between the shear line and corner diagonal position, the effective thickness and flexural rigidity of the wall increase. Further, the shock wave impingement angle charges such pressure levels decrease as is indicated in Volume I of this report.

The increased thickness is given by:

$$h = t/\cos \theta$$

where t is wall thickness

θ is angle-off the corner (degrees)

The reduced pressure can be represented by:

$$p = p_o \cos \theta$$

where p_o is reference pressure.

Since both factors are important, yet mutually exclusive, and breach distance assumed proportional to pressure and inversely proportioned to thickness, product function such as

$$p/k = p_o \cos^2 \theta/t$$

Normalizing for this application, the corner factor becomes:

$$k_c = \cos^2 \theta$$

The recommended procedure to compute breach distance is set forth as follows:

(1) Determine breaching distance for the mid-span per available data.

(2) Decrease the mid-span breaching distance by the factor in the region between mid-span and the shear line as given by k_s.

(3) Use the shear line breach distance between the shear line and outside wall extension.

(4) Decrease the shear line breach distance by the corner factor around the corner to the corner diagonal.

Figure 12 shows breach distance for a 27-pound charge as a function of breaching position around an 8-inch-thick wall.

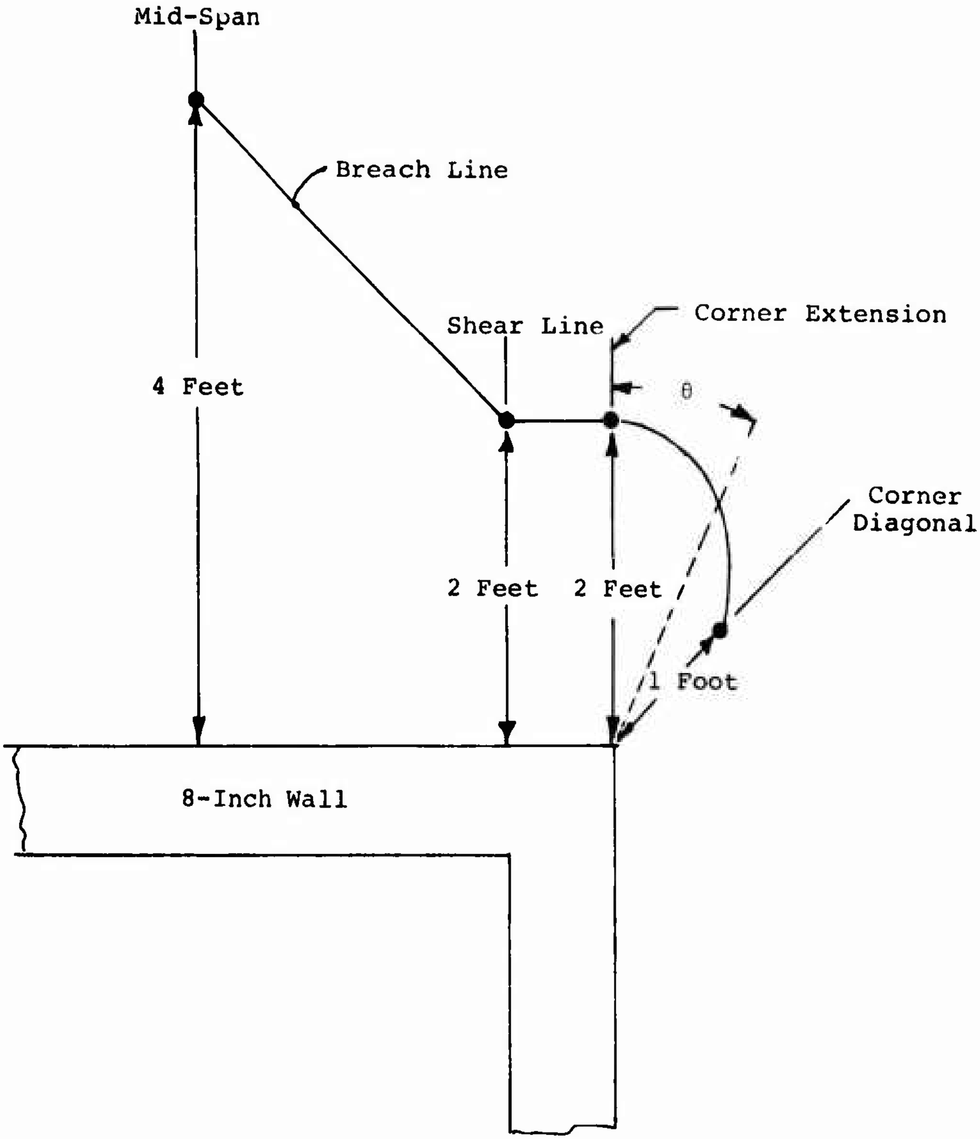


Figure 12. Breach Distance for 8-Inch Wall Box With 27-Pound Charge

SECTION IV
CONCLUSIONS AND RECOMMENDATIONS

The following conclusions and recommendations are based on the 23 tests that were conducted to define breaching distances for various charge weights when detonated near the corner of an underground reinforced concrete structure. The results of 3 tests to establish charge orientation effects are also discussed.

A. CONCLUSIONS

Based on the charge orientation tests, near-field effects are quite evident. Pressures off the end of cylindrical charges are much less than those off the side. Thus, charge orientation must be considered.

As part of the underground structure tests, measurements were made of the pressure levels generated in the free soil. This was done to establish whether pressure levels were being generated consistent with those expected from the C-4 charges. The data showed that pressure decreased as the inverse 2.4 power of scaled distance. This value was in contrast to the inverse cube scaling usually employed. However, with the scatter in the data, the inverse cube was also a realistic relationship for the data although not the best least-squares fit.

Eight of the 23 tests made with the underground reinforced concrete structures resulted in breaching. Two of the eight were corner shots, three were shear line shots, and three were mid-span shots. Simple breaching equations fail to yield a minimum charge weight necessary to breach the corner. A single charge of 27 pounds against an 8-inch-thick wall overkilled the structure while a 10-pound charge did not breach. At the mid-span, a 27-pound charge overkilled with a 2-foot standoff while a 10-pound charge breached at a 1-foot standoff distance. Again, this was in reference to an 8-inch-thick wall.

Two conclusions drawn from this data are:

(1) The minimum charge weight that will do breaching damage must be substantially increased from that predicted from either mid-span breach data or conventional demolition data

when used against a corner. A charge weight of 67.5 times the wall thickness in feet cubed should be considered the minimum charge weight for corner breaching.

(2) If a charge weight exceeds minimums required for breaching in contact, the stand-off distance for breach can be computed, as discussed in subsection III-D.

B. RECOMMENDATIONS

Based on the results of these initial studies, it is reccommended that continued testing be done to better define the effects of several parameters. First, the effect of thickness-to-span ratio for the two percent steel reinforcing structures currently used in contrast to the World War II data generated with one percent reinforcement. Second, charge orientation effects need to be better defined. Since this work is primarily near-field effects, the gaseous detonation products parameters need to be investigated. Specifically, bubble expansion rates off the end and sides of cylindrical charges.

A third parameter which needs to be investigated is the effect of munition casing on soil pressure levels. Bare charge equivalents have been used in these tests, and a need exists to review the effect of encasing these charges.

The fourth parameter which needs to be considered is charge depth. The open-ended structures have had the tests made with charge detonations occurring at structure mid-point in depth. The effect of soil overburden on the structure and over the charge needs to be better defined.

REFERENCE

1. Newmark, N. M. and Haltiwanger, J. D., Air Force Design Manual, Principles and Practice for Design of Hardened Structures. AFSWC-TDR-62-138, Air Force Special Weapons Center, Air Force Systems Command, Kirtland AFB, N.M., December 1962.

APPENDIX A

TEST DATA SHEETS

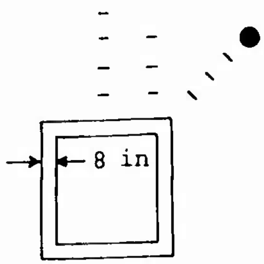
This appendix presents data sheets for each of the 23 experiments conducted in which explosive charges were detonated against underground concrete structures. Each data sheet contains the following information:

1. Weight and stand-off distance of C-4 explosive charge.
2. Target wall thickness (4 or 8 inches).
3. Position of charge relative to target (sketch).
4. Location and data for each pressure gage - in some cases, no data were recorded on one or more gages due to malfunctioning components in the instrumentation system.
5. Photographs illustrating pertinent results of each test.

Section III-B and -C in this report summarize the test results and present analysis of the data.

DATA SHEET FOR TEST NUMBER 1

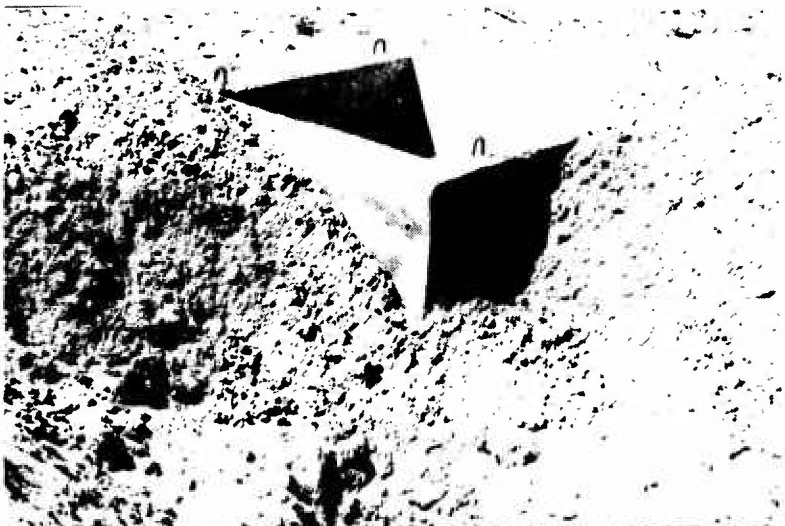
4 Pounds at 4 Feet



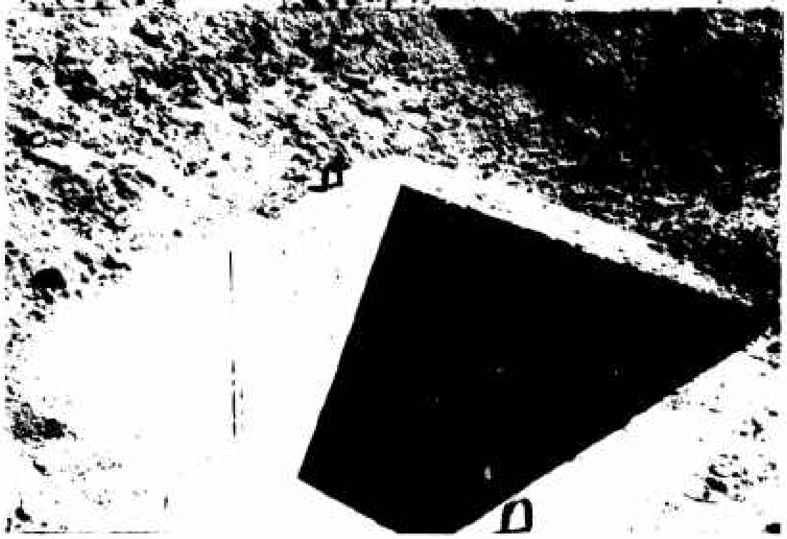
Soil Pressure Gage		Peak Force (lb)	Impulse (lb x ms)
Position	Distance (ft) (1)		
No Data			

1. From CG of explosive to gage surface

1. Index marks at 1-foot intervals
2. ● Denotes charge location



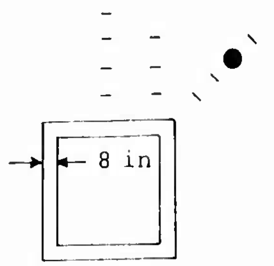
Diagonal View
Outside Corner



Diagonal View
Inside Corner

DATA SHEET FOR TEST NUMBER 2

4 Pounds at 3 Feet



Soil Pressure Gage		Peak Force (lb)	Impulse (lb x ms)
Position	Distance (ft) (1)		
Soil	3.25	466	10,888
Soil	10.9	209	5,351
Wall	5.25	257	14,434

1. From CG of explosive to gage surface

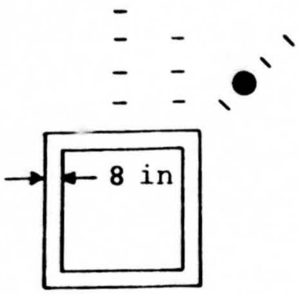
1. Index marks at 1-foot intervals
2. ● Denotes charge location

Diagonal View
Outside Corner

Diagonal View
Inside Corner

DATA SHEET FOR TEST NUMBER 3

4 Pounds at 2 Feet

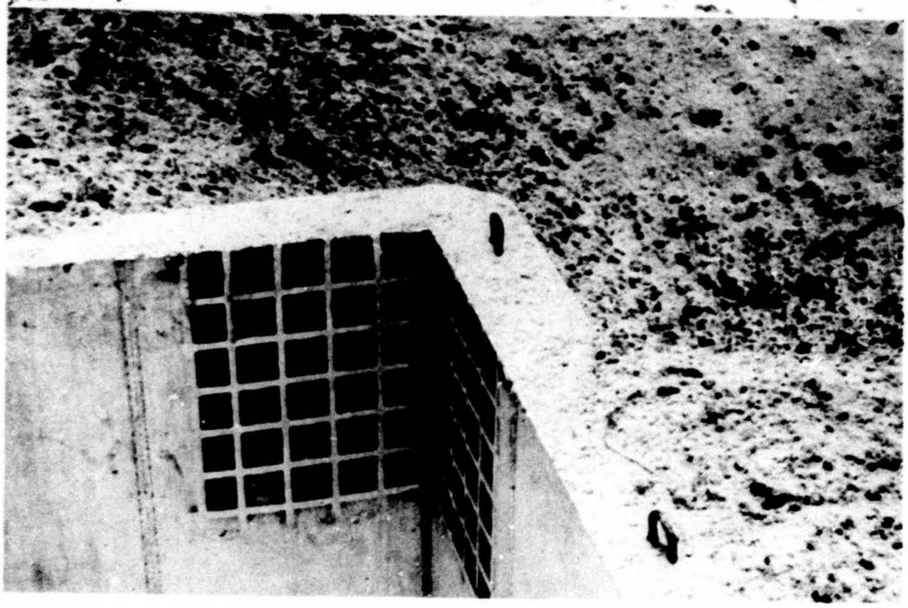


Soil Pressure Gage		Peak Force (lb)	Impulse (lb x ms)
Position	Distance (ft) (1)		
Wall	4.67	361	1,182

1. From CG of explosive to gage surface

1. Index marks at 1-foot intervals
2. ● Denotes charge location

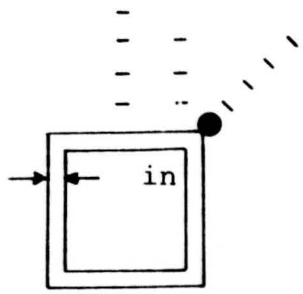
Diagonal View Outside Corner



Diagonal View Inside Corner

DATA SHEET FOR TEST NUMBER 4

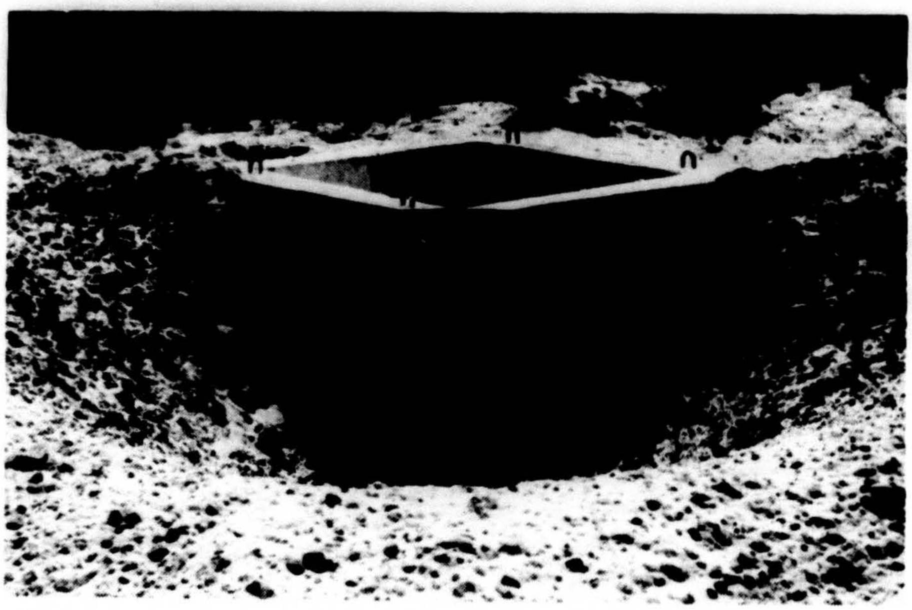
4 Pounds at 0 Feet



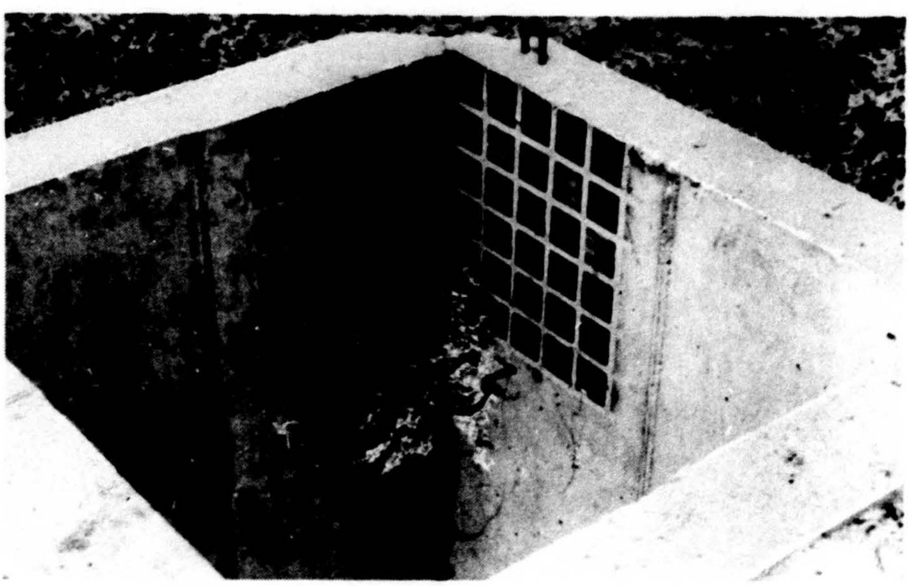
Soil Pressure Gage		Peak Force (lb)	Impulse (lb x ms)
Position	Distance (ft) (1)		
Soil	10	299	8,213
Wall	3	423	2,034

1. From CG of explosive to gage surface

1. Index marks at 1-foot intervals
2. ● Denotes charge location



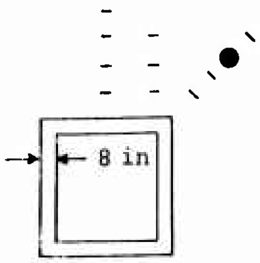
Diagonal View Outside Corner



Diagonal View Inside Corner

DATA SHEET FOR TEST NUMBER 5

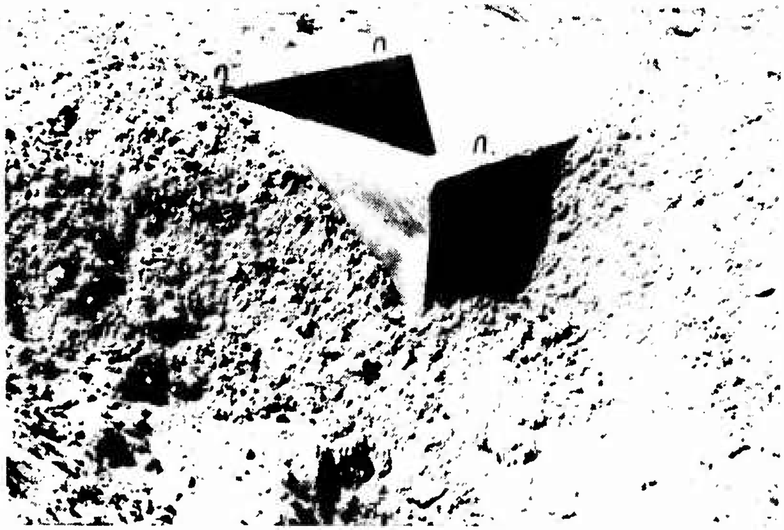
10 Pounds at 3 Feet



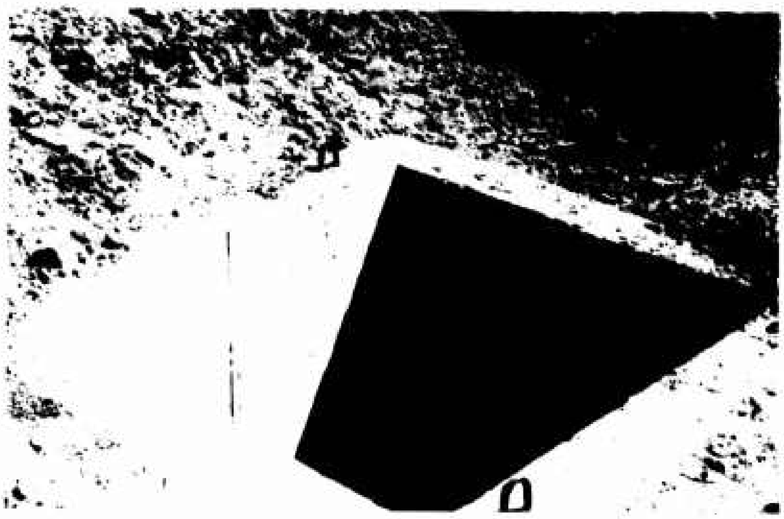
Soil Pressure Gage		Peak Force (lb)	Impulse (lb x ms)
Position	Distance (ft) (1)		
Wall	5.3	748	7,777

1. From CG of explosive to gage surface

1. Index marks at 1-foot intervals
2. ● Denotes charge location



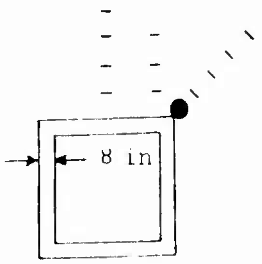
Diagonal View
Outside Corner



Diagonal View
Inside Corner

DATA SHEET FOR TEST NUMBER 6

10 Pounds at 0 Feet



Soil Pressure Gage		Peak Force (lb)	Impulse (lb x ms)
Position	Distance (ft) (1)		
Soil	4.67	1,411	51,950
Soil	10.5	169	2,551

1. From CG of explosive to gage surface

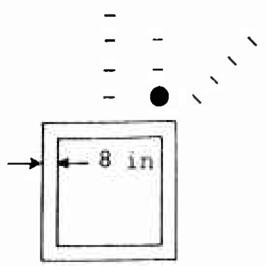
1. Index marks at 1-foot intervals
2. ● Denotes charge location

Diagonal View Outside Corner

Close-up View of Inside Corner Damage

DATA SHEET FOR TEST NUMBER 7

10 Pounds at 1 Feet

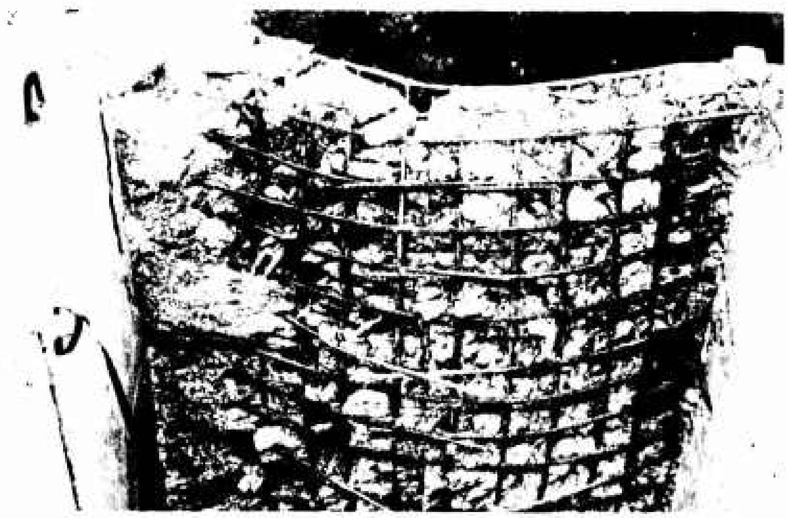


Soil Pressure Gage		Peak Force (lb)	Impulse (lb x ms)
Position	Distance (ft) (1)		
Wall	4.8	722	3,061

1. From CG of explosive to gage surface

1. Index marks at 1-foot intervals
2. ● Denotes charge location

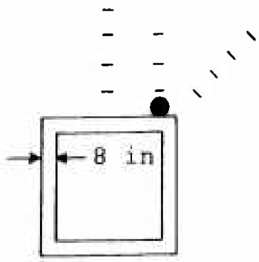
Overall Outside View



Inside Wall

DATA SHEET FOR TEST NUMBER 8

10 Pounds at 0 Feet



Soil Pressure Gage		Peak Force (lb)	Impulse (lb x ms)
Position	Distance (ft) (1)		
No Data			

1. From CG of explosive to gage surface

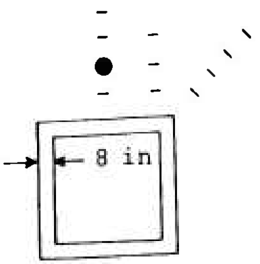
1. Index marks at 1-foot intervals
2. ● Denotes charge location

Shear-Line View Outside

Side View Outside

DATA SHEET FOR TEST NUMBER 9

10 Pounds at 2 Feet



Soil Pressure Gage		Peak Force (lb)	Impulse (lb x ms)
Position	Distance (ft) (1)		
Wall	3.4	3,274	15,368

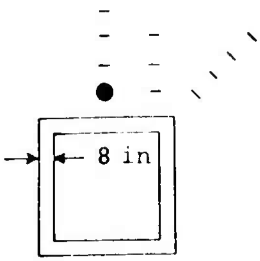
1. From CG of explosive to gage surface

1. Index marks at 1-foot intervals
2. ● Denotes charge location

Side View
Outside

DATA SHEET FOR TEST NUMBER 10

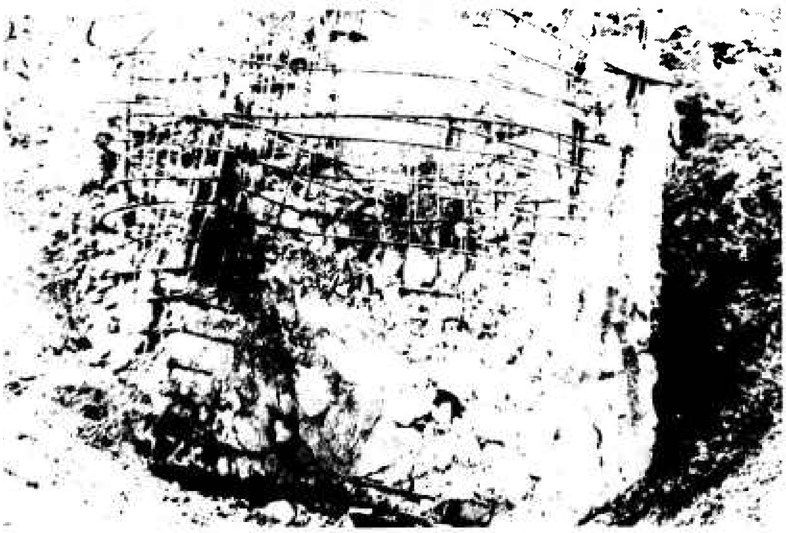
10 Pounds at 1 Feet



Soil Pressure Gage		Peak Force (lb)	Impulse (lb x ms)
Position	Distance (ft) (1)		
No Data			

1. From CG of explosive to gage surface

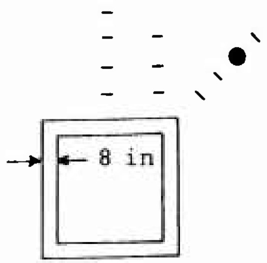
1. Index marks at 1 foot intervals
2. ● Denotes charge location



Overall View

DATA SHEET FOR TEST NUMBER 11

27 Pounds at 3 Feet



Soil Pressure Gage		Peak Force (lb)	Impulse (lb x ms)
Position	Distance (ft) (1)		
Soil	8	282	3,017
Soil	8	621	24,017

1. From CG of explosive to gage surface

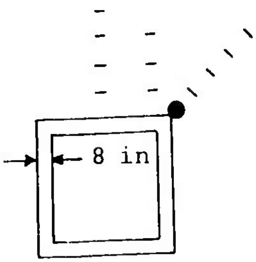
1. Index marks at 1-foot intervals
2. ● Denotes charge location

Diagonal View Outside Corner

Close-up of Corner Crack Pattern

DATA SHEET FOR TEST NUMBER 12

27 Pounds at 0 Feet

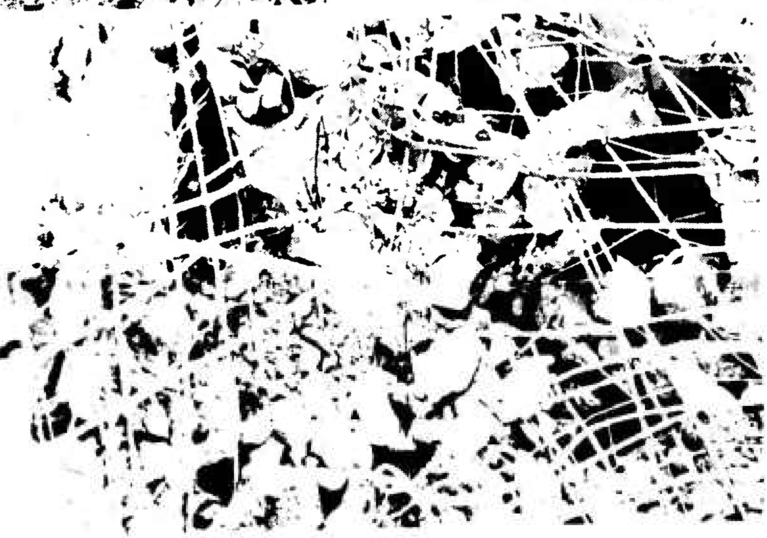


Soil Pressure Gage		Peak Force (lb)	Impulse (lb x ms)
Position	Distance (ft) (1)		
Soil	10.5	705	19,598

1. From CG of explosive to gage surface

1. Index marks at 1-foot intervals
2. ● Denotes charge location

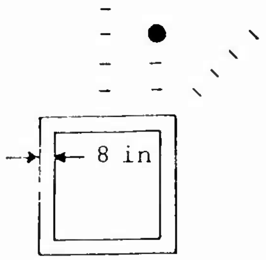
Side View
Outside



Side View
Close-up of
Breach Area

DATA SHEET FOR TEST NUMBER 13

27 Pounds at 3 Feet



Soil Pressure Gage		Peak Force (lb)	Impulse (lb x ms)
Position	Distance (ft) (1)		
Soil	12	339(2)	6,220(2)

1. From CG of explosive to gage surface
2. Highest reading prior to going off-scale

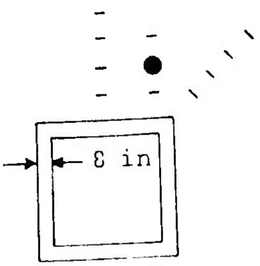
1. Index marks at 1-foot intervals
2. ● Denotes charge location

Side View
Outside

Side View
Inside

DATA SHEET FOR TEST NUMBER 14

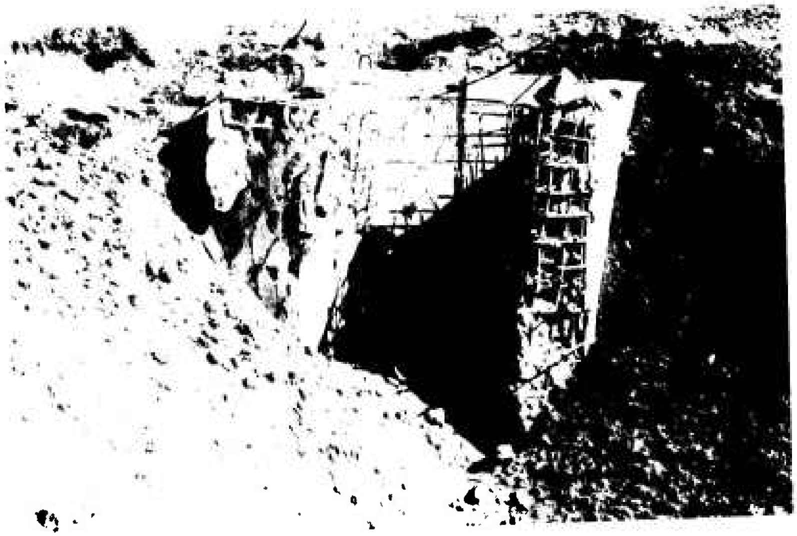
27 Pounds at 2 Feet



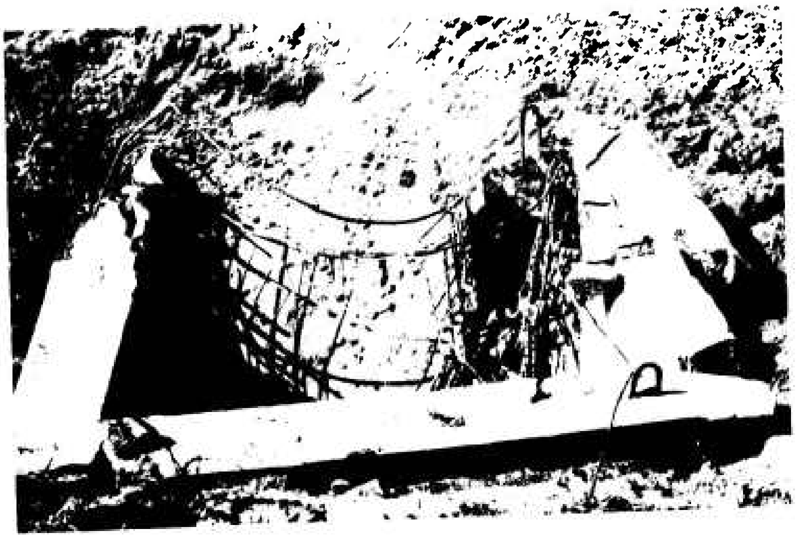
Soil Pressure Gage		Peak Force (lb)	Impulse (lb x ms)
Position	Distance (ft) (1)		
Soil	12	1,208	21,900

1. From CG of explosive to gage surface

1. Index marks at 1 foot intervals
2. ● Denotes charge location



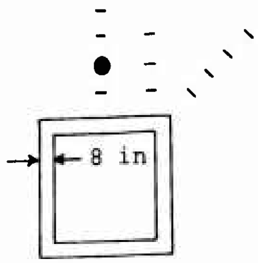
Side View Outside



Side View Inside

DATA SHEET FOR TEST NUMBER 15

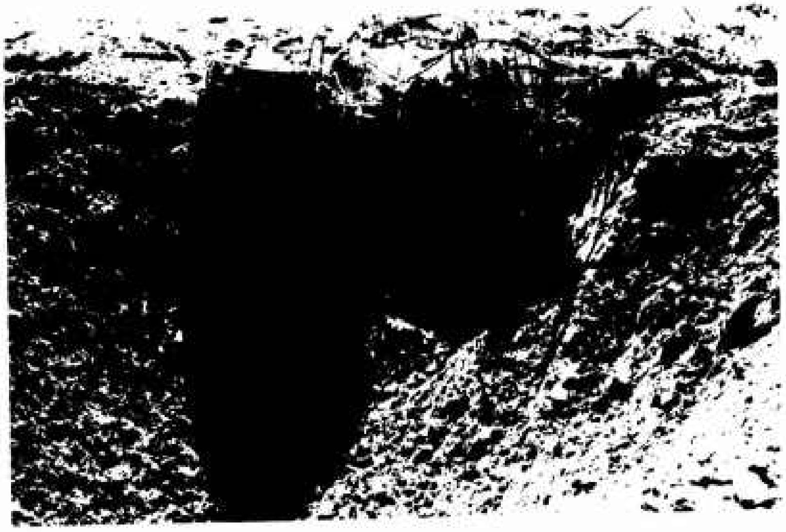
27 Pounds at 2 Feet



Soil Pressure Gage		Peak Force (lb)	Impulse (lb x ms)
Position	Distance (ft) (1)		
Soil	16	127	4,355

1. From CG of explosive to gage surface

1. Index marks at 1-foot intervals
2. ● Denotes charge location

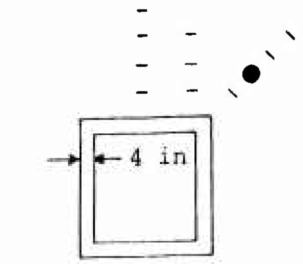


Side View
Outside

Close-up of
Impact Area
Outside

DATA SHEET FOR TEST NUMBER 16

4 Pounds at 2 Feet

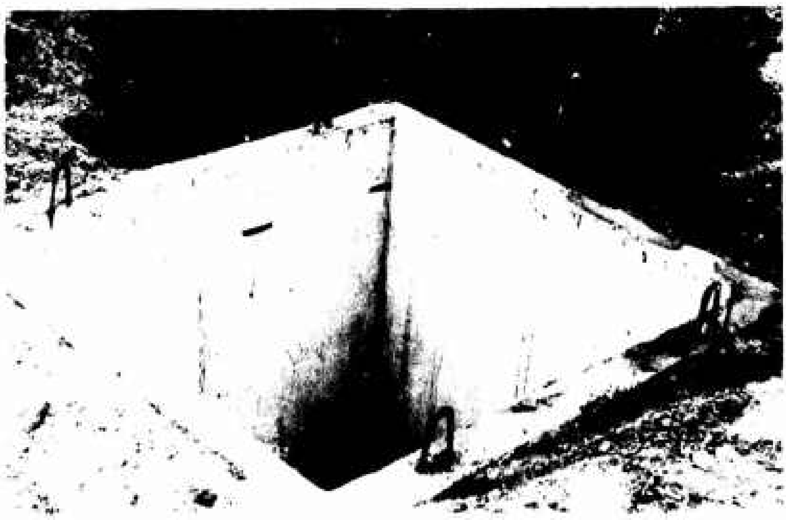


Soil Pressure Gage		Peak Force (lb)	Impulse (lb x ms)
Position	Distance (ft) (1)		
Wall	3.5	1,612	65,610

1. From CG of explosive to gage surface

1. Index marks at 1-foot intervals
2. ● Denotes charge location

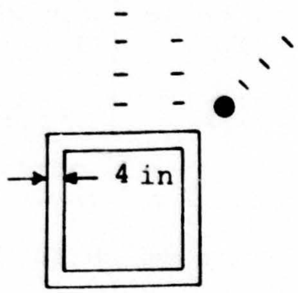
Diagonal View
Outside Corner



Diagonal View
Inside Corner

DATA SHEET FOR TEST NUMBER 17

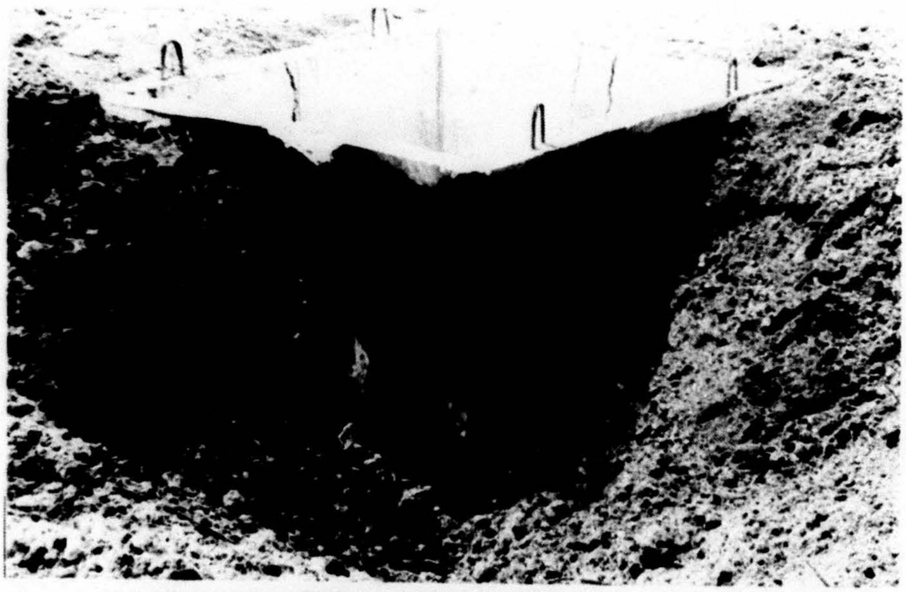
4 Pounds at 1 Feet



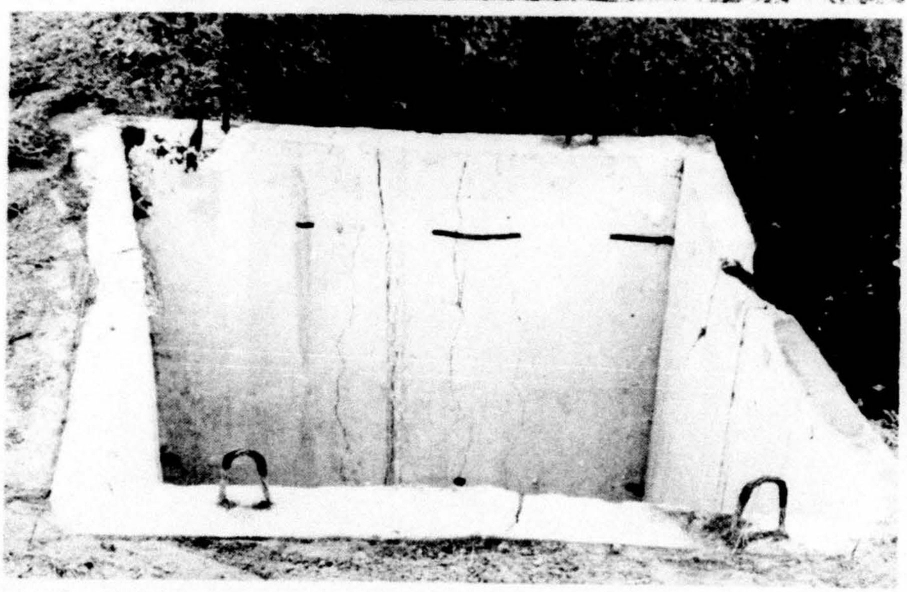
Soil Pressure Gage		Peak Force (lb)	Impulse (lb x ms)
Position	Distance (ft) (1)		
No Data			

1. From CG of explosive to gage surface

1. Index marks at 1-foot intervals
2. ● Denotes charge location



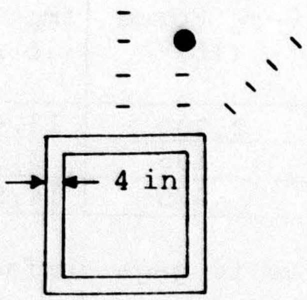
Diagonal View
Outside Corner



Side View
Inside Corner
(Charge on Right
Side of Photograph)

DATA SHEET FOR TEST NUMBER 18

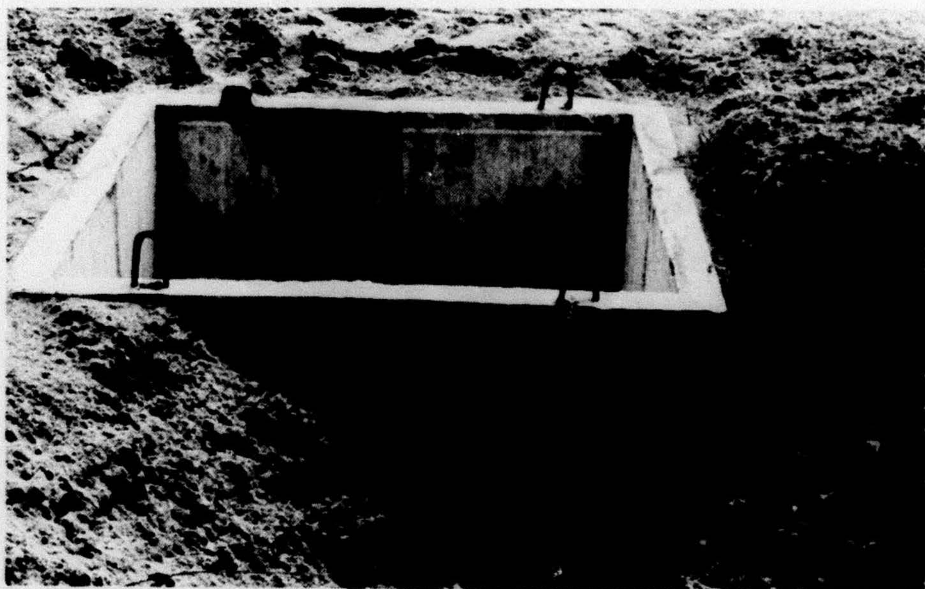
4 Pounds at 3 Feet



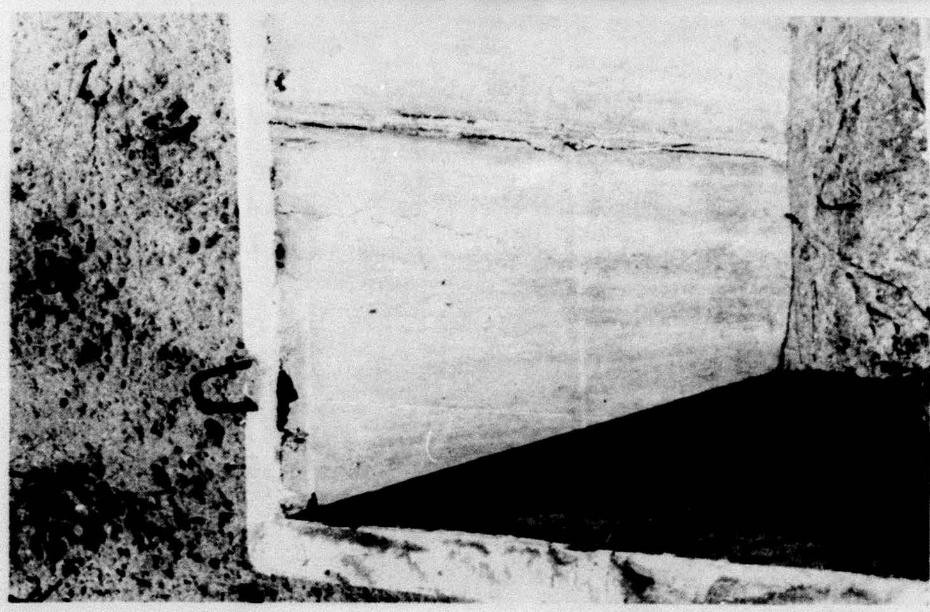
Soil Pressure Gage		Peak Force (lb)	Impulse (lb x ms)
Position	Distance (ft) (1)		
Soil	8	200	6,900
Wall	6	200	6,900

1. From CG of explosive to gage surface

1. Index marks at 1-foot intervals
2. ● Denotes charge location



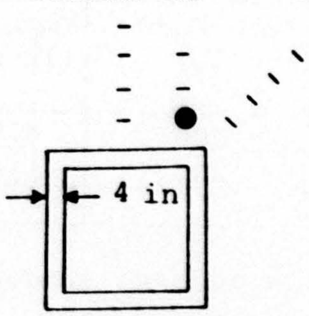
Side View Outside Wall



Side View Inside Wall

DATA SHEET FOR TEST NUMBER 19

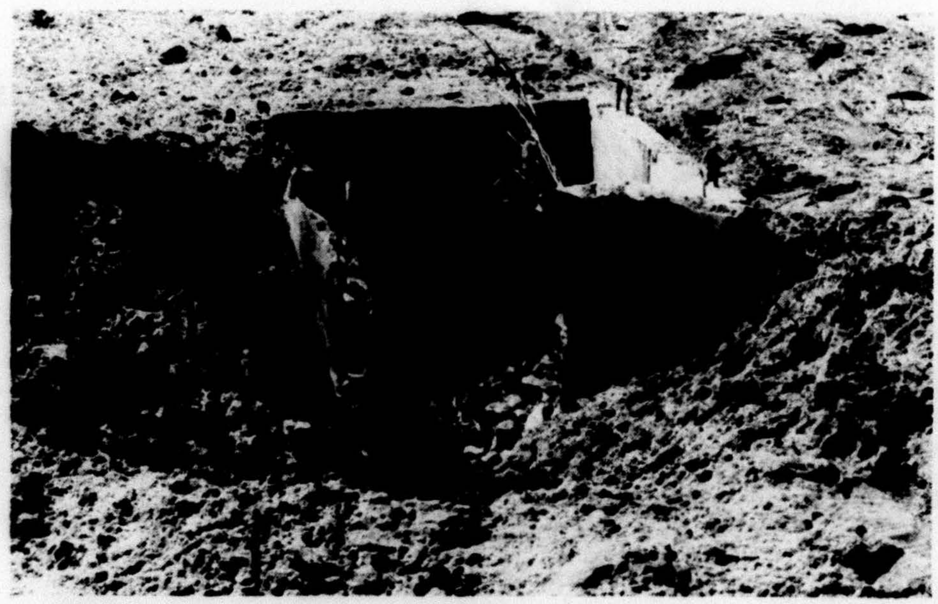
4 Pounds at 1 Feet



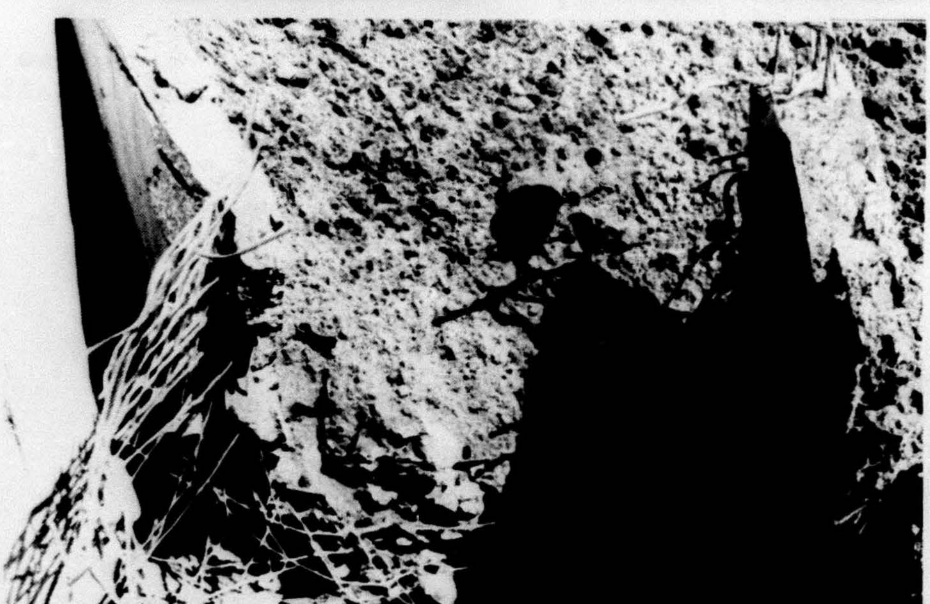
1. Index marks at 1-foot intervals
2. ● Denotes charge location

Soil Pressure Gage		Peak Force (lb)	Impulse (lb x ms)
Position	Distance (ft) (1)		
Soil	4	2,200	14,460
Soil	8	135	3,111
Wall	5.6	675	14,980

1. From CG of explosive to gage surface



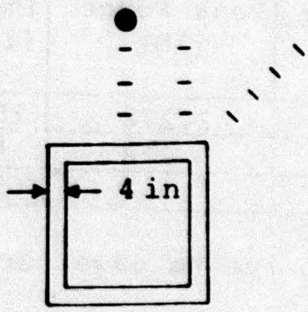
Outside View



Inside View

DATA SHEET FOR TEST NUMBER 20

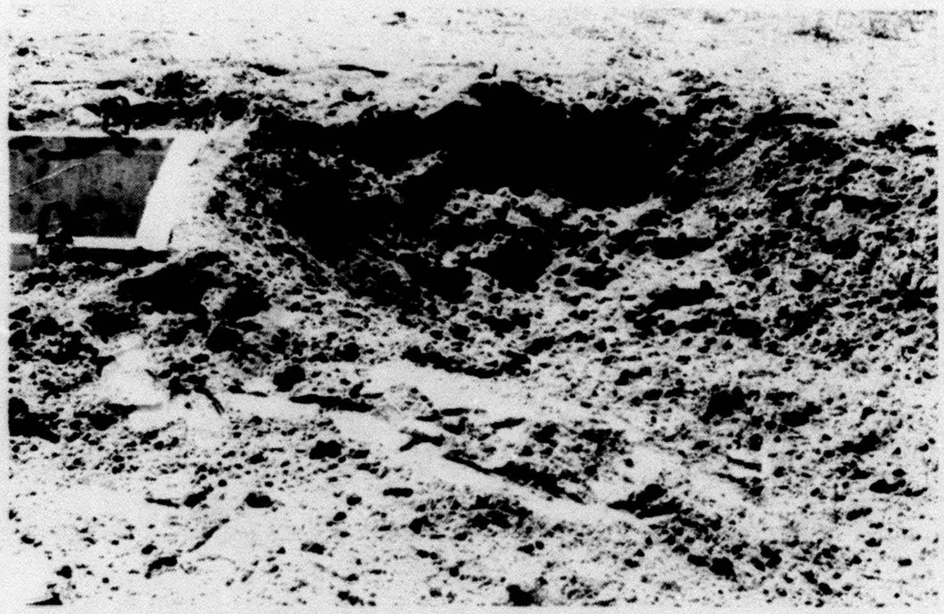
4 Pounds at 4 Feet



Soil Pressure Gage		Peak Force (lb)	Impulse (lb x ms)
Position	Distance (ft) (1)		
Soil	4	1,890	35,263
Soil	8	244	7,250
Wall	4.9	555	15,634

1. From CG of explosive to gage surface

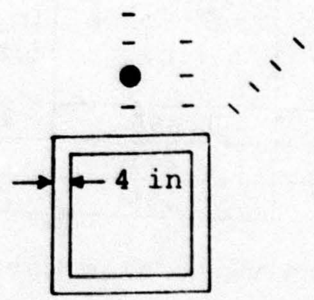
1. Index marks at 1-foot intervals
2. ● Denotes charge location



Overall View

DATA SHEET FOR TEST NUMBER 21

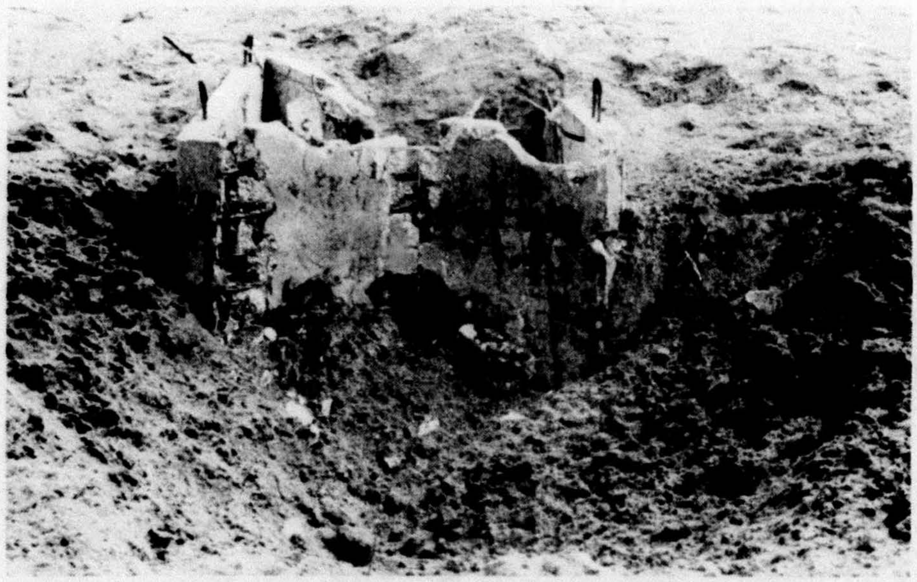
4 Pounds at 2 Feet



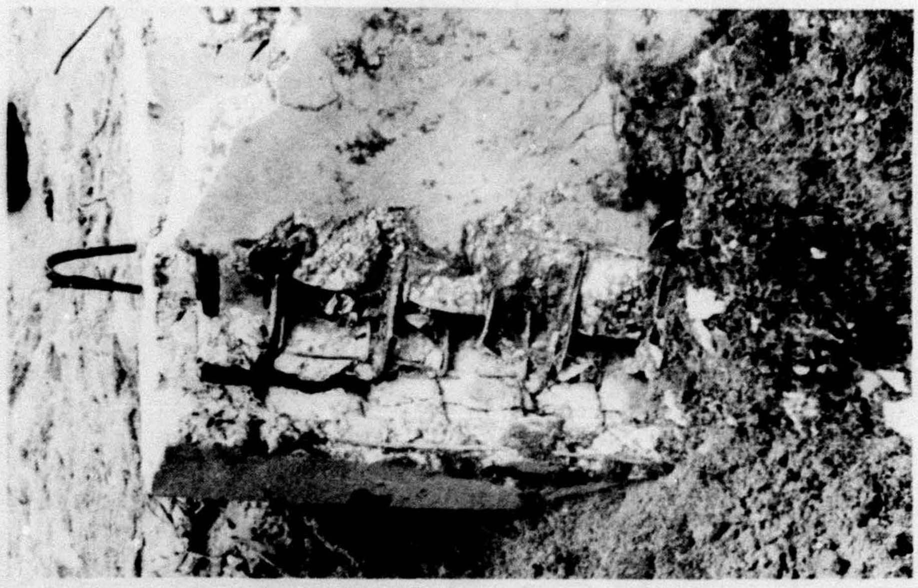
Soil Pressure Gage		Peak Force (lb)	Impulse (lb x ms)
Position	Distance (ft) (1)		
Soil	4	2,278	25,436
Soil	8	278	8,619
Wall	3.5	1,612	65,610

1. From CG of explosive to gage surface

1. Index marks at 1-foot intervals
2. ● Denotes charge location



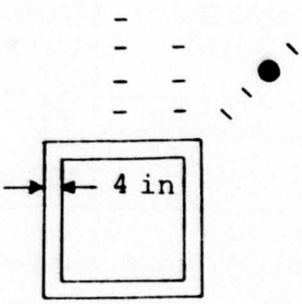
Outside Wall



Close-up of Left Corner Area

DATA SHEET FOR TEST NUMBER 22

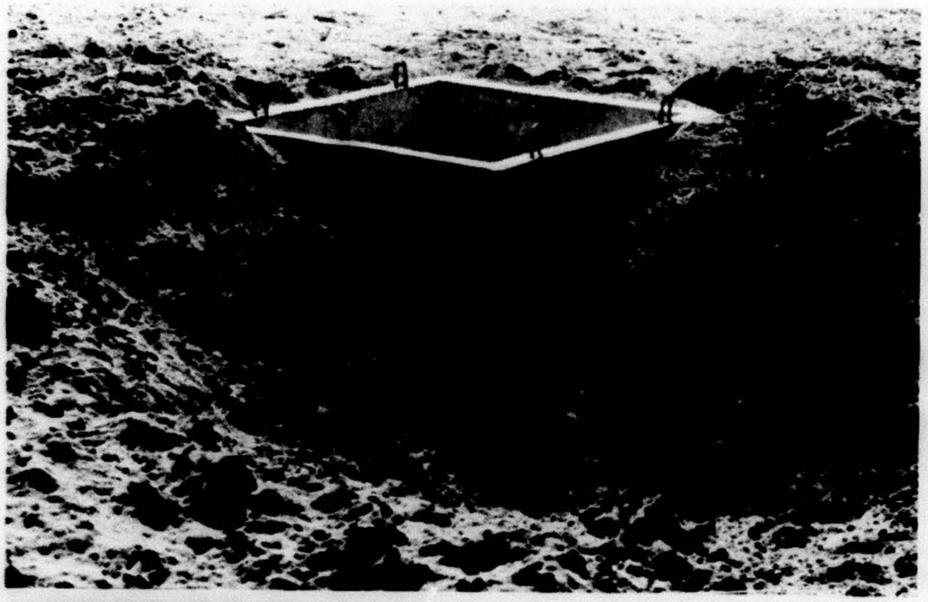
10 Pounds at 3 Feet



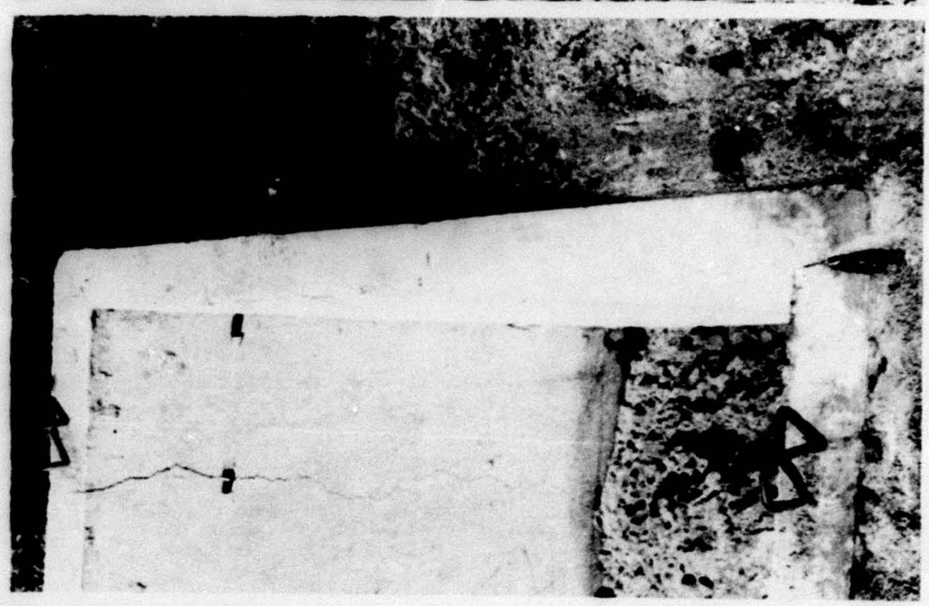
Soil Pressure Gage		Peak Force (lb)	Impulse (lb x ms)
Position	Distance (ft) (1)		
Soil	6	3,000	54,906
Soil	12	212 (2)	3,795 (2)
Wall	5.3	733	

1. From CG of explosive to gage surface
2. Highest reading prior to going off-scale.

1. Index marks at 1-foot intervals
2. ● Denotes charge location



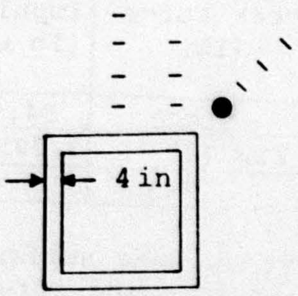
Diagonal View
Outside Corner



Side View Taken
From Left Corner
Looking Toward
Charge

DATA SHEET FOR TEST NUMBER 23

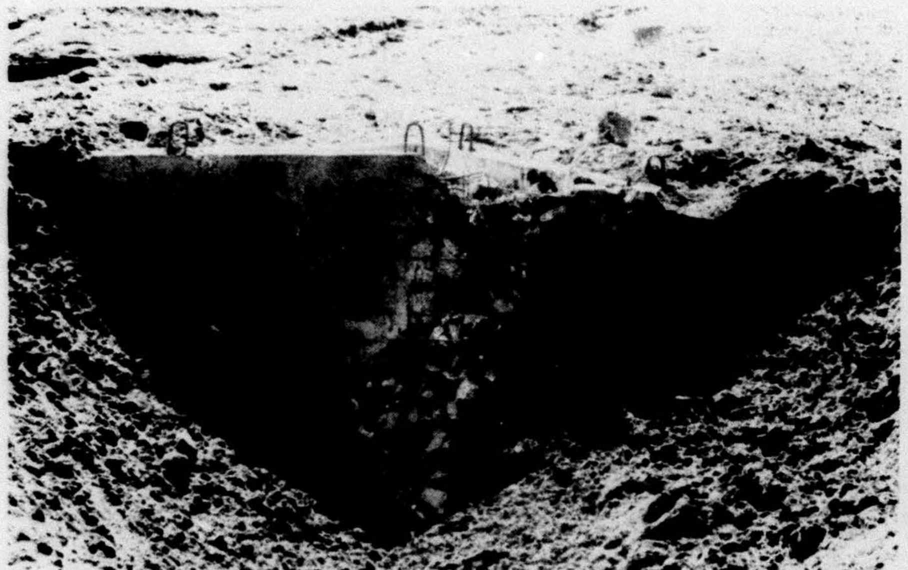
10 Pounds at 1 Feet



Soil Pressure Gage		Peak Force (lb)	Impulse (lb x ms)
Position	Distance (ft) (1)		
Soil	6	1,298	17,598
Soil	12	113	----
Wall	3.5	267	9,870

1. From CG of explosive to gage surface

1. Index marks at 1-foot intervals
2. ● Denotes charge location



Diagonal View Outside Corner

Side View Outside

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